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This dissertation applies general equilibrium techniques to the comparison of two applied environmental policies that are designed to reduce CO_2 emissions: the cap and trade regulatory mechanism and the emissions per output regulatory mechanism. The main objective of this research is to analyze whether one regulation performs better in terms of maximizing overall welfare, applying a general equilibrium framework. Previous research on the effectiveness of environmental policies is inconclusive. The application of general equilibrium analysis contributes to the current literature on the effectiveness of environmental policies, particularly in circumstances in which emissions can leak into other economic sectors or countries.

I conclude that under certain conditions – the separability of inputs in a concave production function and emissions leakage – the optimal policy should regulate emissions per unit of output instead of imposing a cap on emissions. In the main model of this dissertation unilateral cap and trade policies are unable to replicate the first best, and, more importantly, can be an inferior instrument for regulating emissions than a unilateral intensity standard policy. This finding might explain why local policies that regulate emissions per output are in place when there is leakage and a lack of coordination among agents. The results suggest important general equilibrium effects on labor and capital markets.

The hypothetical case of regulating the fossil fuel industry unilaterally in the U.S. shows that a country that regulates will implicitly pay higher endogenous carbon prices than with harmonized cases. Unilateral and incomplete regulation is

costly, both in terms of facing larger endogenous carbon prices and in terms of factor reallocation of capital and labor to unregulated industries and regions. Harmonization of policies across regions and sectors is always preferred, as such policies elicit larger overall welfare. Furthermore, the choice of the regulatory instrument determines the size of the effects. I find evidence that intensity standards are superior to cap and trade mechanisms for incomplete and unilateral regulation cases.

EMISSIONS TAXES VS. INTENSITY STANDARDS REVISITED: A GENERAL EQUILIBRIUM ANALYSIS

by

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Approved by

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Para Victoria

Amada hijita, tú tienes el poder de ser lo que tú quieras. Sé optimista…

¡Nunca te rindas!

APPROVAL PAGE

This dissertation written by Katherine M. Antonio has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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CHAPTER I

INTRODUCTION

Various countries have implemented policies to reduce carbon emissions to achieve long-term goals for emissions reductions and to avoid unwanted consequences of climate change. Research is needed to determine the circumstances in which such environmental policies are effective. Identifying cases in which some policies may be more effective than others could serve to reduce the cost of the implementation of environmental regulations and alleviate the unintended consequences of the regulation, such as the transfer of emissions and production factors to unregulated sectors. Cap and trade mechanisms (or emissions taxes) are the preferred strategy for cutting carbon emissions, mainly because cap and trade can achieve the best possible outcome and restore market efficiency. However, cap and trade requires coordination among participating agents and policymakers to be successfully implemented. Research is needed regarding the general equilibrium effects of implementing unilateral and uncoordinated policies. This dissertation endeavors to illustrate cases in which applying alternative mechanisms, such as emissions per output regulations (or intensity standards), could be superior to using emissions taxes or implementing cap and trade systems.

This dissertation consists of seven chapters and an introduction and a conclusion. In the chapters, I present the economic implications of environmental regulations for the overall economy in different general equilibrium settings. The first chapter presents the introduction, and the second chapter is the literature review. The third chapter examines environmental regulations in practice. In the following two chapters, I present the theory of the general equilibrium model to study the economic implications of carbon emissions regulations under two differing regulatory schemes: cap and trade and intensity standards. I present simulations of this theoretical model and the conditions under which one regulatory scheme is superior to the other. A simple standard general equilibrium model is applied to two countries. Following Fullerton and Heutel (2010), firms in each country produce two goods: one clean good and one dirty good. The production of the dirty good generates emissions as an output that competes for traditional inputs, such as capital and labor. The model is presented in Chapter IV and Chapter V. Chapter IV analytically presents the economic relationships in the model, and Chapter V presents the numerical simulation supporting the analysis as well as a sensitivity analysis. I conclude that under certain conditions – the separability of inputs in a concave production function and emissions leakage – the optimal policy would regulate emissions per unit of output, rather than imposing a cap on emissions.

Chapter VI and Chapter VII expand the analysis by presenting the results of a canonical model analyzing the real world implementation of environmental policies. To do so, the standard general equilibrium model and the Global Trade Analysis Project database (GTAP-Power v10) are used to validate the conclusions presented in the previous chapters.

Chapter VIII takes a complementary approach, comparing welfare under two distinct environmental regulations in the power sector that aim to achieve net-zero emissions targets. To take advantage of the empirical tools in the economic analysis, I present a recursive dynamic multi-country applied general equilibrium exercise, which benefits from using the disaggregation of the power sector in the GTAP-Power 10 database, with a base year of 2014 (Aguiar et al., 2019a). Chapter VIII focuses the analysis of the environmental regulations of greenhouse gasses in carbon dioxide equivalent units (CO_2eq) in the production of energy goods that are carbon intensive, such as electricity generation derived from fossil fuels. Emissions are embedded in the production, import and export of goods. GTAP data presents the trade flows and economic indicators of 76 goods in 141 geographic regions. CO_2 emissions are modeled as a production function employing the production factors listed in GTAP (labor, capital, natural resources, and land) to produce goods. Emissions are also linked to consumer demand. The main focus of this exercise is to analyze the overall welfare effects under various emissions regulatory frameworks of cap and trade regulations and intensity standards regulations. Special attention is paid to the implications of embedded CO_2 on the trade of goods in energy-intensive industries. In addition, goods are imported from labor-intensive countries. The results show that harmonized regulatory approaches are associated to a higher values of overall welfare are also associated to lower endogenous carbon prices. Finally, Chapter IX presents the conclusions of the dissertation.

CHAPTER II

LITERATURE REVIEW

Many papers analyze the effects of environmental taxes and other environmental regulations in a general equilibrium (GE) context. In this chapter, I summarize the literature that focuses on comparing environmental regulations in different settings. Instruments to regulate emissions include emissions cap and trade, performance or intensity standards, emissions taxes, and subsidies for cleaner technologies (Kolstad, 2009).

I focus on two policies in this dissertation: cap and trade and intensity standards. A cap and trade is a regulatory mechanism that sets an overall limit on emissions and regulated entities trade allowances. Intensity standards are a form of regulation of emissions per unit of output. Intensity standards come in different forms, for example, setting a percentage of clean energy in the total electricity generation mix, or setting the ratio of emissions that a country can produce as a percentage of their gross domestic product (GDP). These two policies are adopted in practice and can achieve high welfare outcomes, and these welfare outcomes are extremely important to consider when setting climate policy. However, in practice, there are complexities in designing a proper comparison of instruments. For example, the instruments should be compared by keeping the quantity of emissions they abate equal, or they should be compared on their emissions abatement potential or welfare-maximizing potential.

This chapter contains five sections and includes the main elements for conceptualizing the analysis presented in the dissertation. Section II.1 presents a discussion of global and unilateral policies for reducing carbon emissions, and how these policies are related to leakage. Section II.2 presents the literature review on the limitations of partial equilibrium analysis. Section II.3 discusses the implications of ignoring general equilibrium effects. Section II.4 presents a comparison of cap and trade and intensity standards. Section II.5 presents a discussion about Computable General Equilibrium models and provides an explanation for why these models may be suitable for the analysis of environmental regulations.

II.1. Global v. Unilateral Policies and Leakage

In this section, I discuss the implementation of global and unilateral policies. Global policies may be enablers for achieving an optimal solution for climate change. A cap and trade program is optimal when the cap is set correctly, for example, the limit of emissions can replicate the exact amount of emissions reductions from all parties. In this case, a cap and trade mechanism can emulate the first best. When the cap fully captures the marginal damage of emissions, the cap and trade mechanism sets the correct price and quantity of emissions, that is, fully internalizes the externality of emissions. Thus, regulatory policies require an enormous amount of coordination to achieve the first best.

The marginal damage of emissions is the marginal cost of producing emissions for a society. This marginal social cost represents the marginal external cost to the society, for example, health effects as a results of bad air quality or the effects of pollutants on agriculture. Similarly, the marginal abatement cost of emissions is the associated cost per unit of emissions reductions, which, for example, can be the cost of installing equipment for pollution control.

Leakage of emissions occurs when emissions increase in unregulated regions or industries as a result of the regulation of emissions in another region or industry. When leakage occurs, a cap and trade mechanism may not be an optimal policy. International leakage is a concern because of the difficulty to tax carbon content in foreign goods without violating international trade agreements. Another problem is the difficulty to estimate the amount of CO_2 content in each product that is imported or exported precisely (Shapiro, 2016).

Emissions taxes and cap and trade policies can replicate the first best only if they are set to the optimal level. An intensity standard cannot attain the first best because it cannot both efficiently encourage substitution towards less emissions-intensive sources and reduce consumption. Intensity standards can only attain the first best under very stringent conditions, for example, under perfectly inelastic supply or demand.

Studies focusing on assessing CO_2 regulations at the national or global level have aimed to find the optimal global policy. For example, Sims et al. (2003) emphasize that countries need to migrate to technologies that emit less carbon when generating electricity. The authors found that apart from CO_2 sequestration and power plant technologies, other CO_2 emissions-reduction technologies, such as nuclear and other green energy power plants, were able to lower both the cost of carbon emissions and electricity generation by the present year, 2020 .

One of the challenges of implementing environmental protections unilaterally is that other countries do not share the same regulations, and firms can relocate industrial activities to non-regulated areas. Leakage and incomplete regulation has been explored in various settings, such as implementing the regulation of drilling activities on federal land in the energy sector (Fowlie et al., 2012). Greenhouse gas (GHG) emissions are harmful even if emitted outside of the policy country/region because they are global pollutants. Leakage of emissions sources to unregulated countries/regions is therefore problematic for regulated countries/regions.

II.2. Limitations of Partial Equilibrium Analysis

This section presents the literature that uses partial equilibrium models to compare environmental regulations. According to the United States Environmental Protection Agency's (EPA's) Economic Guidelines, the economic model of partial equilibrium accounts for demand and supply responses in a regulated sector, and partial equilibrium results "may apply to a small number of closely related markets" (EPA, 2014, p.8). For example, partial equilibrium ignores the effects on intermediate products that supply goods and services to upstream markets in regulated areas. The guideline stated that "partial equilibrium analysis is usually appropriate when the scope of a regulation is limited to a single sector, or to a small number of sectors" (EPA, 2014, p.8). Hence, when analyzing the effects of a policy on a particular market, a partial equilibrium analysis will effectively "capture the social cost of the regulation" (EPA, 2014, p. 8) .

Partial equilibrium is often applied to estimate the social cost of emissions when the effects of regulating emissions are related to a small number of markets or a single market. The assumption in partial equilibrium models is that the impacts of regulating pollution in most markets do not affect other markets and can therefore be ignored or assessed using partial equilibrium analysis. Nonetheless, some authors argue that partial equilibrium conclusions are biased when analyzing climate policies. For instance, the results of partial equilibrium studies consistently ignore the effects of a policy on factor prices and the direct or indirect effects on other markets or industries (Goulder and Williams, 2003).

The literature provides estimates of the magnitude of the second-order general equilibrium effects. The second-order effects are mainly in factor prices and factor mobility across industries. Goulder and Williams (2003) explored the bias that results from ignoring general equilibrium (GE) effects, and show that doing so when analyzing taxes on commodities “underestimates the excess burden of commodity taxes, in some cases by a factor of 10 or more”; the authors explain that partial equilibrium is biased “because it ignores general equilibrium interactions—most important, interactions between the taxed commodity and the labor market" (Goulder and Williams, 2003).

Different sectors are expected to experience critical economic effects because of either indirect or direct regulations; thus, a cost-benefit analysis that focuses mainly on how impacts in the directly controlled sector can substantially underestimate the social cost of the regulations. Kokoski and Smith (1987) show that partial equilibrium models lead to significant errors in welfare estimations even when analyzing small policy shocks that affect more than one sector (EPA, 2014). Pizer et al. (2006) also show that implicit biases lead to important differences between general and partial equilibrium estimates of welfare when analyzing carbon pricing for different sectors (Pizer et al., 2006). Hence, as Hahn and Hird (1991) has stated, the critical question to ask is under what conditions it is realistic to ignore these second-order effects. The authors noted that it is difficult to generalize the implications of second-order effects because these vary across regulations and industries (Hahn and Hird, 1991).

II.3. General Equilibrium Effects

In this section, I review the literature that develops theoretical general equilibrium models of emissions and leakage. I also present several applied general equilibrium models of environmental regulations. When determining the best regulatory instrument for environmental regulation, policymakers evaluate a standard set of parameters, such as the cost-effectiveness, distributional equity, uncertainties, and political feasibility (Goulder and Parry, 2008, p. 152) . However, as Goulder and Parry (2008) importantly note, there is no one instrument that is superior along all dimensions that are relevant when choosing between policies (Goulder and Parry, 2008) . General equilibrium effects and economic technicalities are generally overlooked when selecting optimal environmental policies.

General equilibrium effects are important, especially when estimating inter-industry interactions and cumulative effects of changes in investments, factor utilization, and payments. Crucially, they will manifest as indirect effects, reallocating factors across industries or regions. The belief is that the overall social cost of regulations may exceed the compliance cost of regulations when including general equilibrium effects (Jaffe et al., 1995), even though this conclusion is not widely supported. For instance, some studies have found that general equilibrium effects are represented as welfare improvements when accounting for the overall effects of a policy such as tax interactions. Effects on factor prices are overlooked by partial equilibrium (PE) analysis, and so GE is particularly appropriate when there is a reason to believe that a given policy would affect wages or factor payments.

Some of the previous literature regarding the effectiveness of environmental policies under general equilibrium underestimate the importance of general equilibrium analysis. However, the assumptions may vary significantly, and the conclusions may be conditional on certain assumptions and functional forms chosen in the modeling exercise. Some studies have identified small carbon leakages (Burniaux and Oliveira Martins, 2012), the results of which may be driven by the specification of the theoretical model and the method used to solve the model. Fullerton and Heutel (2010); Lemoine (2017) and Fell et al. (2017) all applied numerical exercises, and their conclusions are conditional on the specification of the model, the choice of functional forms, and on the parametrization. When the elements are carefully chosen such that they represent the economy well, the conclusions of GE models are robust and can reveal the economy-wide effects of a given policy.

II.4. Comparisons of Cap and Trade and Intensity Standards

In this section, I present a comparison of cap and trade and intensity standards, and discuss the findings and the tools utilized to analyze environmental regulations. Some economic studies evaluate the effectiveness of policies focusing on unilateral or incomplete environmental regulations. For example, Holland (2012) compared emissions taxes versus intensity standards and examined “second-best environmental policies under incomplete regulation (leakage) or market power in partial equilibrium” (Holland, 2009, p. 1) , concluding that tax regulations on emissions “may not be the best instrument for correcting an environmental externality in the presence of incomplete regulation (leakage)" (Holland, 2012)[1]. The author found that under conditions of incomplete regulation and market power, emissions intensity standards may produce higher welfare benefits compared to any emissions tax. It is unclear whether the results of Holland (2012) still hold under general equilibrium, which may provide more conclusive results of the effects of different regulations under leakage both with and without market power [2].

When comparing auctioned permits with performance standards in the electricity sector in a partial equilibrium analysis, Burtraw et al. (2001) found that the cost of lowering power plant emission of CO_2 with auctioned permits is a third of the cost under performance standards. Auctioned permits have a more significant effect on consumer electricity prices because companies must pay under auctioned permits for the remaining emissions. Thus, auctioned permits help to bring marginal social costs closer to electricity generation prices. In contrast, for performance standards, the regulated utilities cannot pass on the cost of emissions abatement to the consumer, since the utilities do not pay for emissions allowances. Consumers are better off in terms of electricity consumption under performance standards because performance standards yield the lowest electricity price.

Fischer and Newell (2008) evaluated reductions of CO_2 through the implementation of renewable energy technology innovation and diffusion. Using partial equilibrium analysis, Fischer and Newell (2008) found that pricing

[1] Working paper version (unpublished) in `http://libres.uncg.edu/ir/uncg/f/S_Holland_Emissions_2012.pdf`

[2] Other authors found that an intensity standard can dominate the cap and trade instrument because standards encourage substitution towards less emissions-intensive sources but also subsidize output, and are therefore considered to be inferior to the first best solution of a Pigouvian tax or a cap and trade system (Annicchiarico and Dio, 2015; Dissou and Karnizova, 2016; Fischer and Springborn, 2011; Fullerton and Heutel, 2010; Helfand, 1991; Holland, 2012; Holland et al., 2009).

emissions is the most efficient policy to reduce emissions, with the exception of when carbon prices are applied to “ very small emission reduction targets” (Fischer and Newell, 2008, p. 160). Additionally, a combination of regulations, instead of a unique regulation, can reduce the costs significantly, especially when ‘R&D subsidies are included’ (Fischer and Newell, 2008).

Fullerton and Heutel (2010) used a general equilibrium approach and a Harberger GE model in a closed economy. In their model, pollution was included as an input in the production function “that can be a complement or substitute for labor or capital” (Fullerton and Heutel, 2010, p. 64) . The results of their simulations show that stricter regulation does not necessarily favor the utilization of the factor that is a substitute for pollution. Fullerton and Heutel (2010) described that intensity standards create an “output-subsidy effect”; that is, there is an implicit subsidy on factor prices that may offset the traditional output and substitution effects . Capital utilization may increase production of the dirty good. The authors found that strict regulation does not always allocate the burden to a better substitute of pollution and may instead represent an implicit subsidy on the prices of capital and labor “that can reverse the output and substitution effects” (Fullerton and Heutel, 2010).

Burniaux and Oliveira Martins (2012) analyzed the effectiveness of unilateral action to regulate carbon emissions under a GE framework, focusing on estimating the size of carbon leakages in a two-region, two-goods model in the energy sector. They found that “coal supply elasticity plays a critical role, while substitution elasticities between traded goods and international capital mobility appear relatively less influential” (Burniaux and Oliveira Martins, 2012, p.473) . In their model, the “unilateral carbon abatement action” (adopted by some developed countries) was offset by significant carbon leakages to the non-participants' regions (Burniaux and Oliveira Martins, 2012). However, their conclusion should be interpreted with caution. The specification of the production function and the method used to solve the GE model also plays a large role in determining the leakage amount (Burniaux and Oliveira Martins, 2012). Burniaux and Oliveira Martins (2012) claimed that the parametrization of the model played a critical role in informing their conclusions, and that small leakages can favor the formation of a worldwide coalition to stabilize climate change.

Karp (2012) analyzed the general equilibrium effects of unilateral environmental regulations, and established that "the general equilibrium effects of stricter environmental policy might reinforce or moderate the policy's partial equilibrium effects" (Karp, 2012, p.1). He concluded that the effect is ambiguous in trading patterns and pollution levels, resulting in both positive and negative leakage (Karp, 2012). However, he also concluded that unilaterally stricter policies lead to a reallocation of the factors of production, creating an income and a production effect (Karp, 2012).

Most recent research on the optimal environmental regulatory policy adopts the macroeconomic perspective. For example, Annicchiarico and Dio (2015) studied the "dynamic behavior of an economy under different environmental policy regimes in a New Keynesian model with nominal and real uncertainty" (Annicchiarico and Dio, 2015, p.1). The authors found that an emissions cap policy probably reduces macroeconomic fluctuations, and price adjustment significantly alters the results of the environmental policy (Annicchiarico and Dio, 2015). Other authors have used a "multi-sector business cycle model to analyze the stochastic implications of reducing CO_2 emissions with carbon permits or with carbon taxes in the presence of multiple sources of macroeconomic uncertainty” [3]. Dissou and Karnizova (2016) found that cap regulation reduces the volatility of real variables more than tax regulation does. The authors found that welfare is higher when using a tax than when using a cap and is more sensitive when the shocks are applied to the energy sector (Dissou and Karnizova, 2016).

Lemoine (2017) examined third-best policies in general equilibrium, and found that an instrument that “regulates the carbon intensity of transportation and electricity markets” by maximizing welfare is not optimal (Lemoine, 2017). The author argues that “the regulator can achieve a higher level of welfare by manipulating the emission ratings than by manipulating the level of the standard” (Lemoine, 2017).

II.5. Computable General Equilibrium Analysis and Environmental Regulations

In this section, I present the concept of Computable General Equilibrium (CGE) models and how they are applied to the analysis of environmental regulations. CGE models are a class of models that rely on computational capabilities to solve economic problems. As opposed to purely theoretical economic GE models and concomitant simulations, CGE models are built to replicate the economic relationships in an economy; the models are based on actual economic aggregates combined with other data sources. CGE models rely on computational optimizers to solve a system of equations or perform

[3] Using a real business cycle model in 2011, Fischer and Springborn (2011) found that the cap hinders the effects of productivity shocks in the economy, while some intensity targets are associated with higher levels of labor, capital, and output.

constrained optimization. They generally solve problems complex in nature, with multiple interactions and have no analytical solution.

CGE models have been employed by both national and international institutions to the assess economic and environmental impacts of policies that aim to control carbon emissions, among other greenhouse gases (Döll, 2009; Fullerton and Heutel, 2010). These policies may include introducing taxes to the emitters. Döll (2009) and Bhattacharyya (1996) present a survey of CGE models that were used to evaluate the impact of environmental and energy policies in the United States. CGE models are especially useful for quantifying the effects of a policy, or for estimating the effect of a percentage increase/decrease on other economic variables. Furthermore, they are also useful for approximating the dollar value of an economic aggregate since they are calibrated to real-life economic aggregates.

Economy-wide models are applied in long-run sustainability analysis. The fundamentals of economy-wide models are a set of national accounts that capture "a complete set of inter-industry and inter-regional relationships in the global economy in a consistent manner" (Peters and Hertel, 2016, p. 11). Economy-wide models are used to assess the effects of real-life environmental policies.

Dozens of economy-wide models are currently employed to analyze dynamic economic projections and emissions in the United States, including ADAGE, AIM, ARIMAX, DART, EC-MSMR, ENGAGE, ENVISAGE, ENV-Linkages, EPPA, EU-EMS, EXIOMOD, FARM, GAPS-EnVISAGE, GDYN, GEM-E3, GLOBIOM, GNET, ICES, IGEM, IMACLIM-R, ISSA, JRC-GEM, MAGNET, MESSAGE, MIRAGE-e, MIRAGRODEP, MONASH, PACE, REMIND, TEA, USAGE, etc. A recent effort led by economists has attempted to compare the macro assumptions, parameters, and trade relationships of these models (Bekkers et al., 2018, p. 11).

Several papers focus on the effects of emissions reduction targets resulting from international cooperation agreements, such as the United Nations International Panel of Climate Change (IPCC) where countries compromised on emissions reductions targets, either a percentage emissions reduction from a baseline, or a limit to emissions with respect to the country's GDP.

Increased renewable sources for generating electricity "requires distinct electricity generating technologies in a CGE database" (Peters, 2016a). In practice, CGE models are useful for quantifying the effects of energy and environmental policies. For example, the U.S. EPA applies CGE models to conduct cost-benefit analysis for all economically significant[4] policies. The use of CGE provides an assessment of the overall effect of the policies and quantifies the social benefits and costs of environmental regulations with respect to a benchmark[5].

CGE models are capable of simulating relevant policy issues on climate, such as budgetary concerns and the accumulation of public debt, which is similar to most traditional models (Nordhaus and Yang, 1996). CGE models are a flexible tool for the analysis of climate policies, and some models include spatial and regional analysis to better assess the heterogeneity across regions and variations in climate (Jahn, 2014). Dynamic CGE models present features such as endogenous economic growth paths and are applied to real-life economic analysis. Dynamic CGE models, in combination with the TIMES[6] model and the

[4]Economically significant is defined by the EPA as those regulations with "costs and/or benefits estimated of at least $100 million in a single year" (EPA, 2014)

[5]`https://www.epa.gov/environmental-economics/cge-modeling-regulatory-analysis`

[6]`https://iea-etsap.org/index.php/etsap-tools/model-generators/times`

CGE model, are used to examine subsidies on renewable energy and the taxation of CO_2 by regulators.

One requirement to construct a CGE model is having a database that represents the main aggregates of the economy. The data from CGE models should consist of a consistent database contained in the Social Accounting Matrix (SAM), combined with alternative sources of information to construct a baseline that represents the steady state in the economy. For the analysis of environmental policies, economy-wide CGE models focus on the linkages of emissions to the main economic sectors in a country and the interactions of the gains and losses of environmental policies among countries. For example, researchers from the Global Trade Analysis Project (GTAP) at Purdue University have developed a variety of data sets that are used as the primary data for the analysis of global policies. The GTAP project provides a variety of models and data[7]. One of the GTAP's databases contains "a disaggregation of the electricity sector into electricity-generating technologies", which is called the GTAP-Power Data Base. The GTAP-Power data is an extension of the standard GTAP data providing an electricity-detailed disaggregation to include transmission and distribution, nuclear, coal, gas, hydroelectric, wind, oil, solar, and other technologies. Some of the technologies are further disaggregated by base and peak load. The disaggregation is based on information about electricity generation and the levelized cost of electricity (Chepeliev, 2020c).

With the increased use of renewable technologies, electric power substitution has acquired more relevance in the literature. The substitution of fuels is modeled as a nested structure in CGE. For example, the production of

[7]https://www.gtap.agecon.purdue.edu/about/data_models.asp

electricity will be represented as a nest with capital, labor, and energy sources as inputs. A nest will assume some form for the elasticity of substitution, for example, Peters (2016a) assumes an “additive constant elasticity of substitution” arguing that this form “ensures that the sum of demands for generation from each technology is equal to total demand for electricity generation” (Peters, 2016a, p.156) .

II.6. Conclusions

This literature review presents the relevant concepts related to the comparison of environmental regulations and the setting in which these regulations are compared. To compare cap and trade and intensity standards, several factors should be considered, particularly the fact that regulating emissions and imposing other environmental regulations will affect labor markets, capital, and trade. Different regulatory instruments will have different impacts on overall welfare, economic growth, trade, and labor markets, and the various linkages and outcomes must be considered when crafting any public policies designed to reduce CO_2 emissions.

This literature review has also shown that the differences between partial and general equilibrium modeling are significant. For example, in the partial equilibrium model, the assessment of a policy shock affecting two or more interconnected markets assumes that the rest of the economy remains fixed (the *ceteris-paribus* condition). Thus, partial equilibrium analysis ignores the effects of a policy on other markets, including markets that constitute intermediate inputs of the market being analyzed. On the other hand, CGE models aim to simulate and assess policies with economic consequences that may affect several markets.

CHAPTER III

ENVIRONMENTAL REGULATIONS IN PRACTICE

This chapter discusses a wide range of policy options for regulating emissions, including cap and trade or carbon taxes, and intensity standards, in addition to command and control policies. Countries have implemented a number of different approaches to regulate emissions. In addition to cap and trade and intensity standards, which are the focus of this dissertation, I also discuss command and control and market based policies.

Among the policy tools that regulators can apply are command and control (CAC) policies and market-based policies. Command and control policies imply that the regulator sets the method and distributes the abatement among emitters. However, in market-based policies, the regulation is based on incentives, where the emitters can perform transactions and trade pollution permits.

This chapter contains five sections. First, I present the applications of a cap and trade scheme. Second, I present a brief discussion and examples of carbon taxes. Third, I discuss different applications of intensity standards. Fourth, I discuss command and control policies. Fifth, I present a brief discussion of international climate agreements.

III.1. Cap and Trade

In this section, I present examples of the application of the concept of cap and trade to current regulations. Emissions targets are emissions reductions with respect to a historical baseline. Regulatory policies were adopted in the United States to regulate emissions using the market through trading. For example, the

Acid Rain Program established by the Clean Air Act (Title IV) is the most extensive cap and trade program in the United States. The U.S. EPA manages the Acid Rain Program using a cap and trade system to reduce emissions from power generation and coal power plants. The program has the objective of reducing emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x).

Another example of an emissions trading policy in the United States is the Regional Clean Air Incentives Market (RECLAIM), which allows an emissions trading scheme in Southern California (EPA, 2019). The RECLAIM program, which "was adopted by the South Coast Air Quality Management District (SCAQMD) in 1993" (EPA, 2019), sets limits on NO_x and sulfur oxides (SO_x) in the South Coast Air Basin (EPA, 2019). There were around 258 RECLAIM participants in 2018 (Fowlie et al., 2012). The U.S. EPA report shows that emissions fell by approximately 18% under the program (EPA, 2019)[1]. Fowlie et al. (2012) compared facilities in locations where the RECLAIM program was implemented with equivalent facilities in California and estimated a 20% reduction in emissions in the participating facilities.

The Regional Greenhouse Gas Initiative (RGGI) was implemented in the United States as a mandatory policy with the objective to reduce emissions from the electricity sector[2] The RGGI program cap was set to 91 million short tons in 2014, and the target reduced by 2.5 percent each year from 2015 to 2020 (RGGI, 2020)[3]. The monetary value of the RGGI initiative from January to November

[1] https://www3.epa.gov/region9/air/reclaim/ and http://www.aqmd.gov/docs/default-source/reclaim/reclaim-annual-report/reclaim-2017-audit-report.pdf?sfvrsn=12

[2] The states participating in RGGI are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont

[3] https://www.rggi.org/

2019 is $258.68 million (see Table III.1)[4].

The Western Climate Initiative (WCI) has the objective "to reduce regional GHG emissions to 15% below 2005 levels by 2020" (Western Climate Initiative, 2019). Among its goals, the WCI has "to spur investment and development of clean-energy technologies, create green jobs, and protect public health" (Western Climate Initiative, 2019). The WCI is a regional cap and trade program in the power sector. The program is composed of three Canadian states, British Columbia, Quebec, and Nova Scotia, along with California[5]. The Cross-State Air Pollution Rule (CSAPR) is an example of a policy in place that limits SO_2 and NO_x emissions for around 22 mostly Eastern states. States can exceed their budget by trading with other states subject to variability limits (EPA, 2020b). In the United States, local regulations are applied and are reviewed on a regular basis. The rule is aimed to limit power plant emissions that cause leakage of pollution across states (EPA, 2020b)[6].

Internationally, the European Union (EU) Emissions Trading System (ETS) applies cap and trade policies (European Commission, 2020). A limit on the total amount of emissions that can be emitted is set and reduced over time so that total emissions fall over time. Companies trade emissions allowances. After each year, companies are required to have allowances of at least the amount used in the year; otherwise, they pay a fine (European Commission, 2020). If a company has a surplus of allowances, the company can keep them for future needs or sell

[4]The associated government revenue for the RGGI program was $239.36 million from January to November 2019. The year when RGGI reached the maximum associated government revenue was in 2013 with $447.97 million (World Bank, 2020).

[5]`http://www.wci-inc.org/`

[6]`https://www.epa.gov/airmarkets/final-cross-state-air-pollution-rule-update#additional-resources`

them to another company. The EU ETS operates in all EU countries, along with Iceland, Liechtenstein, and Norway. The target includes “emissions from more than 11,000 heavy emitters energy-using installations” (European Comission, 2015), such as power plants, industrial plants, and airlines, and it is estimated to cover “around 45% of the EU’s greenhouse gas emissions” (European Comission, 2015)[7]. A recent study of the EU ETS has found “no evidence of carbon leakage in European manufacturing” (European Commission, 2020).

The overall value of the global carbon markets closed at around $214.5 billion by the end of 2019 (Global and Platts, 2020)[8]. The EU ETS is currently “the world’s biggest emissions trading market, accounting for over three-quarters of international carbon trading” (European Commission, 2020)[9]. The average carbon price in the EU ETS increased to 25 Euros per metric ton in 2019 from 16 Euros per metric ton in 2018, as a result of the tightened supply of allowances (World Bank, 2020).

Carbon markets are expected to grow in 2020 with the start of China’s national ETS, which will initially cover the electricity sector (International Carbon Action Partnership, 2020)[10]. China has implemented eight regional pilot emissions trading systems since 2013, reaching an approximate value of $0.56 billion as of November 2019 (World Bank, 2020). This is expected to cover 4.4 billion metric tons of CO_2 equivalent.

According to the information published (WB, 2020), the ETS and carbon

[7] https://ec.europa.eu/clima/sites/clima/files/docs/ets_handbook_en.pdf

[8] https://www.spglobal.com/platts/en/market-insights/latest-news/coal/012320-global-carbon-markets-grow-34-in-2019-led-by-europe-refinitiv

[9] https://ec.europa.eu/clima/sites/clima/files/factsheet_ets_en.pdf

[10] https://icapcarbonaction.com/en/?option=com_etsmap&task=export&format=pdf&layout=list&systems\%5B\%5D=55

pricing initiatives covered 11 gigatons of CO_2 equivalent globally in 2019, representing 20.1% of the global GHG emissions for the same year. ETS initiatives on their own have covered eight gigatons of CO_2 equivalent emissions, which is 15.0% of global GHG emissions.

Table III.1 shows the emissions trading policies that are currently implemented around the globe and that have been formally adopted through legislation. If realized this year, China would take the lead in terms of GHG emissions covered. The Chinese market is expected to cover around 6% of global CO_2 emissions, which represents more than three thousand million metric tons of CO_2 equivalent. North America's ETS markets are relatively smaller compared to Europe or China if realized. California cap and trade (C&T)[11] covers the largest amount of emissions. In terms of GHG emissions covered, the California C&T program is about three times larger than the entire RGGI initiative. In terms of value, California C&T traded around $5 billion in 2019, while the entire RGGI only traded $0.26 billion. California C&T is a comprehensive initiative that encompasses "electricity generators (within California), electricity importers, industrial facility operators and fuel distributors" (RGGI, 2020). In the case of Australia, the ETS mechanisms is not similar to a cap and trade system, but to a "baseline-and-offset" system, which explains why the monetary value is not included.

[11]https://www.c2es.org/content/california-cap-and-trade

Table III.1. Emissions trading system (ETS) initiatives: January to November 2019

Name of the initiative	Year of implementation	GHG emissions	Proportion of global GHG emissions (%)	Value ($ billion)	Initiative with overlapping GHG emissions covered	Overlaping covered GHG (MtCO2e)
East Asia & Pacific						
China national ETS	2020	3,231.90	5.94%	–	China national ETS	440.8
Guangdong pilot ETS	2013	366.30	0.67%	1.23	China national ETS	128.2
Fujian pilot ETS	2016	200.00	0.37%	0.30	China national ETS	70.0
Shanghai pilot ETS	2013	169.69	0.31%	0.71	China national ETS	59.4
Hubei pilot ETS	2014	162.09	0.30%	1.06	China national ETS	56.7
Tianjin pilot ETS	2013	118.25	0.22%	0.33	China national ETS	41.4
Chongqing pilot ETS	2014	97.24	0.18%	0.06	China national ETS	34.0
Beijing pilot ETS	2013	84.65	0.16%	0.56	China national ETS	29.6
Shenzhen pilot ETS	2013	61.20	0.11%	0.02	China national ETS	21.4
Tokyo C&T	2010	13.92	0.03%	0.01	Japan carbon tax	13.9
Saitama ETS	2011	7.91	0.01%	0.01	Japan carbon tax	7.9
Korea ETS	2015	468.29	0.86%	12.30	Korea ETS	
Australia ERF	2016	380.84	0.70%	–	Australia	
New Zealand ETS	2008	39.85	0.07%	0.49	New Zealand	
Europe and Central Asia						
EU ETS	2005	2,131.84	3.92%	45.52	Finland carbon tax, Ireland carbon tax, UK carbon price floor, Norway carbon tax	169.4
Kazakhstan ETS	2013	183.25	0.34%	–	Kazakhstan	
Switzerland ETS	2008	5.95	0.01%	0.03	Switzerland	
North America						
California C&T	2012	377.69	0.69%	5.46	California	
Alberta CCIR	2007	124.80	0.23%	0.34	Alberta	
RGGI	2009	103.14	0.19%	0.26	Massachusetts ETS	10.2
Canada federal OBPS	2019	82.09	0.15%	–	Canada	
Quebec C&T	2013	68.85	0.13%	0.90	Quebec	
Washington CAR	2017	57.81	0.11%	–	Washington	
Virginia ETS*	2020	36.93	0.07%	–	Virginia	
Nova Scotia C&T	2019	15.20	0.03%	–	Nova Scotia	
Massachusetts ETS	2018	14.27	0.03%	–	RGGI	14.3
Saskatchewan OBPS	2019	8.64	0.02%	–	Saskatchewan	
Newfoundland and Labrador PSS	2019	4.26	0.01%	–	Newfoundland and Labrador	

Source: Own elaboration based on the information of the Carbon Pricing Dashboard published by the World Bank, 2019
Abbreviations
GHG: Grenhouse gases, $MtCO_{2Eq}$: Metric Tons of Carbon Dioxide Equivalent. C&T: Cap and Trade, CCIR: The Carbon Competitiveness Incentive Regulation, RGGI: The Regional Greenhouse Gas Initiative, OBPS: OutputBased Pricing System, CAR: Clean Air Rule, PSS: Price Support Scheme.

III.2. Carbon Taxes

In this section, I discuss the implementation of carbon taxes and how the concept is related to carbon price. In practice, emissions taxes are implemented to tax carbon directly by establishing an explicit carbon price. Carbon taxes are currently operating in different countries and economic sectors. Under carbon taxes, companies are charged a monetary value for the amount of emissions they produce. Companies have to pay the tax and cannot trade with other entities to increase or reduce their allowances. Both emissions taxes and the cap can replicate the first best when they are set to fully capture the marginal social damage of emissions, and if this is the case, regulating with a cap is equivalent to imposing a carbon tax and vice-versa[12].

Table III.2 shows the regions where carbon taxes are currently in place, the amount of GHG emissions covered, and the monetary value. As compared with ETS, carbon tax initiatives cover smaller amounts of GHG emissions and are smaller in terms of monetary value. Japan is the leader in terms of carbon taxation, covering around a thousand metric tons of CO_2 with an equivalent monetary value of more that $2 billion. The carbon pricing initiatives are categorized into either ETSs or carbon taxes according to how they operate technically (WB, 2020). The initiatives do not follow the two categories strictly in terms of design or sector coverage (WB, 2020); the principal objective of the table is to provide a sense of the quantity of emissions and trade covered by the current initiatives.

[12]The main difference between the two is that with a carbon tax, the carbon price is determined exogenously (i.e., by the government). However, with emissions trading the carbon price is determined endogenously (i.e., by the market).

Table III.2. Carbon pricing initiatives: January to November 2019

Name of the initiative	Year of implementation	GHG emissions covered (MtCO2e)	Proportion of global GHG emissions (%)	Value ($ billion)	Initiative with overlapping GHG emissions covered	Overlaping covered GHG (MtCO2e)
East Asia & Pacific						
Japan carbon tax	2012	999.43	1.84%	2.36	Tokyo C&T, Saitama ETS	22.71
Singapore carbon tax	2019	42.02	0.08%	0.15		
Europe and Central Asia						
Ukraine carbon tax	2011	287.01	0.53%	0.10		
France carbon tax	2014	175.63	0.32%	8.14	EU ETS	
UK carbon price floor	2013	136.45	0.25%	0.98	EU ETS	136.45
Norway carbon tax	1991	39.56	0.07%	1.71	EU ETS	11.78
Ireland carbon tax	2010	30.79	0.06%	0.49	EU ETS	12.32
Sweden carbon tax	1991	26.14	0.05%	2.49	EU ETS	–
Finland carbon tax	1990	25.09	0.05%	1.46	EU ETS	9.28
Denmark carbon tax	1992	21.59	0.04%	0.55	EU ETS	–
Portugal carbon tax	2015	20.80	0.04%	0.29		
Switzerland carbon tax	2008	17.98	0.03%	1.20		
Poland carbon tax	1990	15.54	0.03%	0.00		
Spain carbon tax	2014	9.02	0.02%	0.10		
Slovenia carbon tax	1996	4.96	0.01%	0.08		–
Latvia carbon tax	2004	2.06	0.00%	0.01	EU ETS	–
Iceland carbon tax	2010	1.59	0.00%	0.05	EU ETS	–
Estonia carbon tax	2000	0.76	0.00%	0.00	EU ETS	–
Liechtenstein carbon tax	2008	0.06	0.00%	0.00		
Latin America						
Mexico carbon tax	2014	307.33	0.56%	0.32		
Argentina carbon tax	2018	79.25	0.15%	0.18		
Chile carbon tax	2017	46.67	0.09%	0.17		
Colombia carbon tax	2017	41.62	0.08%	0.10		
North America						
Prince Edward Island carbon tax	2019	0.92	0.00%	0.01		
Newfoundland and Labrador	2019	4.51	0.01%	0.05		
British Columbia carbon tax	2008	42.70	0.08%	1.24		–
Canada federal fuel charge	2019	179.73	0.33%	1.99		
Sub-Saharan Africa						
South Africa carbon tax	2019	412.87	0.76%	0.17		

Source: Own elaboration based on the information of the Carbon Pricing Dashboard published by the World Bank , 2019
Abbreviations
GHG: Grenhouse gases, $MtCO_{2Eq}$: Metric Tons of Carbon Dioxide Equivalent. C&T: Cap and Trade, ETS: Emissions Trading System.

III.3. Intensity Standards

In this section, I discuss a wide variety of intensity standards that are applied locally to different sectors and regions. Emissions intensity targets are policies that specify emissions reductions relative to output (i.e., tons of CO_2 per million dollars of GDP). Emissions reductions targets, on the other hand, specify reductions measured in metric tons, relative to a baseline (WRI, 2006).

Examples of emissions standards are the Low Carbon Fuel Standard (LCFS), the Renewable Portfolio Standard (RPS) and the Renewable Fuel Standard (RFS), which are implemented by amendments of the Clean Air Act (CAA).

California established the LCFS program with the goal of reducing emissions by 20% in the average carbon intensity of fuel by 2030. The LCFS program started in 2011 and determines an average carbon content for fuels and sets annual reductions. To comply, “companies need to either change the balance of fuels they sell or buy credits to offset emissions” (Board, 2020, p.1) .

A study of the LCFS program shows that “the standard implicitly subsidizes all fuel sources” (relative to the first best solution), while it decreases the carbon intensity of transportation fuels, and as a result the overall consumption of energy may increase (Holland et al., 2009). With the help of a numerical exercise, Fell et al. (2017) analytically show and that intensity standards can replicate the first best when incorporating energy efficiency in rate-based emissions intensity standards. Their claim is based on a perfectly inelastic energy demand.

Under the RPS, companies have to generate a portion of their electricity using renewable electricity sources (EIA, 2020a). By December 2018, 29 states and the District of Columbia have implemented RPS. The states of California, Hawaii, Maine, Nevada, New Mexico, New York, Washington, and the District of Columbia set a target of 100% of electricity from clean sources by 2050 (EIA, 2020a). Each state decides on the standards differently under the RPS. Most differences across states are in the characterization of renewable electricity, “perhaps due to the ambiguity of the externality associated” with the standard

(Holland, 2012). Figure III.1 shows the states in which RPS policies are applied, the percentage, and the year of the target for each state.

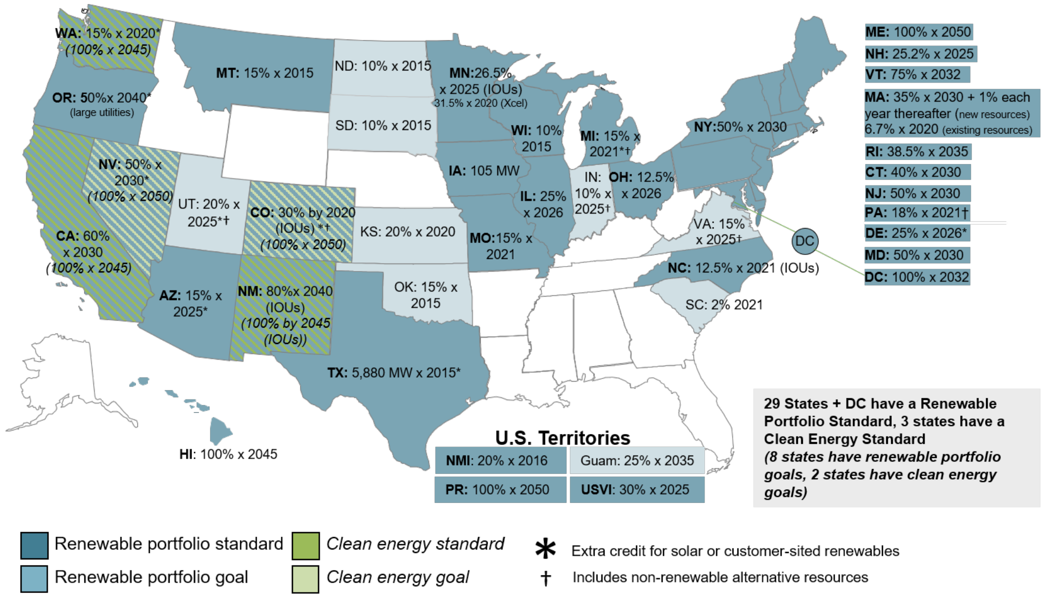


Figure III.1. Renewable Portfolio Standards

Source: Extracted from North Carolina Clean Energy and Technology Center -DSIRE
`https://www.dsireusa.org/resources/detailed-summary-maps/`

The RFS program sets the minimum levels of renewable energy in motor fuel so that companies have to produce a percentage of renewable energy in their composition, thereby allowing trading of the emissions among companies. The RFS program is a national policy implemented in 2005 and reformulated in 2007 under the Energy Independence and Security Act (EISA) (EPA, 2020c).

Another intensity standard in the United States is the Corporate Average Fuel Economy Standard (CAFE), which is set to reduce the per-unit fuel consumption of vehicles. Administered by the National Highway Traffic Safety Administration, among other targets, CAFE standards set the penetration of clean technologies in gasoline engines, and the current absolute standard is set to 54% for 2025 (of Transportation, 2016).

In June 2019, the EPA repealed the Clean Power Plan initiative and issued the final Affordable Clean Energy (ACE) rule[13]. The ACE rule establishes emissions guidelines for states to implement plans to improve the heat rates of their coal-fired power plants with the aim of reducing CO_2 emissions.

Prior to the ACE rule under the Clean Power Plan rule, the regulator set goals for CO_2 emissions rate reductions by 2030. States were to choose the regulatory mechanism that they would use to reduce emissions, and participation was voluntary. With the help of a numerical exercise, Bushnell et al. (2017) show the conditions under which companies may adopt standards or an emissions limit, and claim that choosing standards may be an optimal strategy for both consumers and electricity generators, especially when "uncoordinated policies that lower welfare and increase emissions relative to coordination" exist (Bushnell et al., 2017, p.57).

A clean energy standard (CES) is a policy that would require certain percentage of utility sales associated to clean energy sources to generate electricity, such as renewables and nuclear. Other sources, such as coal or natural gas, are considered part of the standard when using carbon capture technologies. A percentage of the electricity generated by the utility would receive credits that can be traded. Currently, CESs are included in the draft of the Climate Leadership and Environmental Action for our Nation's (CLEANs) Future Act, a piece of legislation that aims to achieve net-zero greenhouse gas pollution in the United

[13] https://www.epa.gov/stationary-sources-air-pollution/affordable-clean-energy-rule

States by 2050 at the "lowest cost to electric energy consumers" (Energy and Commerce, 2020). In the bill, "carbon intensity" refers to the "carbon dioxide equivalent emissions associated with the generation of 1 megawatt hour of electric energy" for electric companies (Energy and Commerce, 2020). The bill includes the determination of clean energy credits that represent the total quantity of electric energy, in megawatt-hours, consumed during the year, "that is provided by the retail electricity supplier or by a behind-the-meter generation system" (Energy and Commerce, 2020).

III.4. Command and Control

This section presents a brief discussion of command and control (CAC) regulations. Among the policy tools that regulators can apply are CAC policies and market-based policies. CAC policies imply that the regulator sets the method and distributes the abatement among emitters. In contrast to market-oriented policies, CAC regulation is not based on incentives, and emitters cannot perform transactions or trade pollution permits.

CAC regulations are applied in two forms: 1) performance standards and/or technology standards, and/or 2) technology restrictions (e.g., installation of scrubbers on electric power plants or catalytic converters in automobiles). Much of the literature argues that incentives are more cost-effective than CAC restrictions, since market-based regulations equate the marginal abatement cost across firms (Fullerton, 2001; Tietenberg, 2006).

In 1990, the Clean Air Act (CAA) was amended from the 1955 original version, including the National Ambient Air Quality Standards (NAAQS) and the Acid Rain Program. Air quality regulations are mainly targeting the electricity and transportation sectors. The U.S. transportation sector is the primary source of ozone emissions. The U.S. electricity sector is the primary source of NO_x and SO_2 emissions. The EPA definition of criteria pollutants includes the following pollutants: particulate matter, photochemical oxidants and ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead (EPA, 2020a). These are all regulated under the CAA through NAAQS, which regulates emissions of pollutants that harm human health and cause damage to animals, crops, and vegetation (EPA, 2020a). The NAAQS are set as a limit of pollutants, such as parts per million/billion of in relation to volume, and micrograms per cubic meter of air. Geographical areas are tested in terms of air quality, and if an area is "in compliance with the National Ambient Air Quality Standards", the area is classified as an attainment area. Areas that are not in compliance are classified as nonattainment areas (EPA, 2020a).

III.5. International Climate Policies

This section presents a discussion of how the lack of agreement in favor of global and more coordinated policies can have consequences for the efficiency of the policies. Policymakers across the globe have become increasingly aware of the need to control the adverse effects of climate externalities. In the past, there were two important attempts to implement coordinated global policies to reduce carbon emissions: the Kyoto Protocol of 1997 followed by the Paris Agreement of 2015. The current lack of consensus could be because these previous policies could not deliver the desired results in terms of emissions reduction, and because of the lack of agreement among participants; local policies were significantly spread out, as documented in the previous section. This lack of coordination came at significant cost, and in some cases it will require countries to rethink the effectiveness of their preferred regulations.

The requirement to lower CO_2 emissions to reduce global warming has gradually been accepted as a global policy goal. The International Panel for Climate Change (IPCC) effort to reach a global agreement started in Rio de Janeiro as part of the United Nations Framework Convention on Climate Change (UNFCCC) in 1993, and 25 United Nations Climate Change Conferences (UNCCC) have been held all over the world since. The Conference of Parties (COP) is the institution that represents all parties at the Convention. Countries are called Parties to the Convention and are represented at the COP. The purpose of the COP is to agree on the policies to reduce carbon emissions.

The Kyoto Protocol aimed to reduce emissions in developed countries. The fundamental principle of the protocol was the "common but differentiated responsibility and respective capabilities" of countries. The principle recognized the fact that developed countries produced higher levels of emissions in the atmosphere as compared to developing countries. The initial target was set to achieve a 5% emissions reduction by 2012, as compared to 1990 levels. Thirty-six industrialized countries committed to this target.

The Paris Climate Agreement of 2015 mainly focuses on limiting global warming to below 3.6°F by 2100, which is expected to be achieved if states set their targets for lowering CO_2 emissions. Several countries have signed this agreement in documents called National Determined Contributions (NDCs)[14]. The NDCs are a variety of policies determined by countries to reduce emissions, mostly from electricity generation, industry, and transportation sectors. Some of the NDCs take the form of a cap on emissions, and others are intensity standards. Most of the countries have a combination of policies and targets. For example, in

[14] https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx

their first pledge, China's NDCs included the pledge to install 200 gigawatts of wind power and 100 gigawatts of solar power by 2020 (of Climate Change and of China, 2015)[15]. This includes a percentage of renewable energy sources in the country's generation mix. India, for instance, "pledged to reduce the emissions intensity of its GDP by 33 to 35 percent by 2030 from 2005 level", combined with measures to achieve energy efficiency (of Environment and of India, 2016)[16], which, in other words, means that the country will specify emissions reductions relative to productivity or economic output (measured in tons of CO_2 per million dollars of GDP).

Lack of coordination of environmental regulations have significant costs. Some regions are implementing their own schemes to reduce carbon emissions. Research documents how unilateral policies were implemented in the absence of coordinated action, and what the consequences of this uncoordinated action have been. For example, Bushnell et al. (2017) compared different regulatory policies in the electricity sector as a result of the application of the Clean Power Plan. They find that, in some cases, they found that trade and environmental regulations interacted in such a way that they undermined the efficiency of the policies Bushnell et al. (2017). For instance, when a cap and trade regulation is combined with rate standards for generation, the ranking of preferred generating technologies deviates from the efficient choice. Their findings show that consumers and producers may have different preferences over the regulation scheme, and when states implement their own policies to meet the emissions

[15] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/China\%20First/China\%27s\%20First\%20NDC\%20Submission.pdf

[16] https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/India\%20First/INDIA\%20INDC\%20TO\%20UNFCCC.pdf

reduction targets, the lack of coordination leads to large inefficiencies (Bushnell et al., 2017). Thus, in practice the theoretical prescriptions about the optimality and efficiency of environmental regulations is constantly challenged by the complexity of implementing such policies.

III.6. Conclusion

Based on the review of environmental regulations applied in practice, there is no consensus on which policy or policies might be optimal. In theory, a cap and trade program is optimal when the cap is set correctly; however, the coordination and information required to set the target correctly makes it very difficult to implement an appropriate cap. The dynamics of the economy may also require frequent revisions of the targets to ensure that they are binding. For this dissertation, it is important to consider real-life cases where there are no harmonized regulatory policies, and also explore leakage, in both unilateral and harmonized cases. A cap and trade mechanism may not be an optimal policy from the review of the instruments in place. Under the current circumstances of leakage and unilateral regulation, a suboptimal policy, namely intensity standards, is believed to dominate the cap and trade mechanism.

CHAPTER IV

A THEORETICAL MODEL OF EMISSIONS TRADING AND INTENSITY STANDARDS

This chapter aims to present the main model of the dissertation. First, I describe the model set-up, the business as usual and first best scenarios, and define functions and parameters. Second, I formalize the Business as Usual and First Best equilibria. Third, I present the implementation of policies to reduce carbon emissions, namely cap and trade and intensity standards. Finally, I present the conclusions.

The theoretical model aims to explore the cases in which second-best policies could dominate the cap and trade mechanism in terms of maximizing overall welfare. I use a simple static general equilibrium model for an open economy to compare intensity standard regulations (the limit of emissions per unit of output) with the cap and trade mechanism.

In this model, there are two countries producing two different final goods: a relatively cleaner good and a relatively dirtier good. The clean and dirty goods are substitutes in consumption, and a representative consumer in each country with identical preferences consumes both goods. To measure overall welfare, I use a representation of aggregated utility as the summation of the utility for each individual country.

Both countries produce the final homogeneous goods under perfect competition with identical production technologies, and both goods use capital and labor as production factors. The dirty good involves producing carbon emissions, which can be thought of as an intermediate good, an input, or an output.

In this chapter, I assume the two countries have identical input endowments and trade both *Good 1* and *Good 2*. The environmental damage associated with a given trade policy is well defined. Other approaches can be followed as in Bohringer and Rutherford (2008) who impose an endogenous utility transfer between countries to eliminate rent-seeking strategic behavior, so that one country cannot use environmental regulations to extract rents from the other country.

The environmental externality is analyzed by allowing countries to either regulate or not regulate the production of the dirty good. The purpose of this is to allow countries to differ only in their effort to reduce carbon emissions while producing both clean and dirty goods. To isolate the effect of the environmental regulation in the analysis requires exploring the circumstances under which countries can achieve maximum welfare while regulating and trading the dirty good. I analyze two regulation possibilities to cut emissions on the production of the dirty good: cap and trade and intensity standards. To simplify the analysis, I assume the same damage function for both countries; however, the construction of the model allows for testing different combinations of our assumptions. Allowing the countries to differ in initial endowments, behavioral parameters, or combinations of regulations is straightforward.

IV.1. Business as Usual and First Best

The theoretical model consists of two countries indexed by $c \in \{A, B\}$, namely *Country A* and *Country B*. Decisions are made by individuals, consumers, firms, or industries acting in their own self-interest. Consumers maximize utility, and firms maximize profits. There are two production sectors indexed by $i \in \{1, 2\}$. Each country produces two goods, denoted by q_{ic}; the clean good is *Good 1* and the dirty good is *Good 2*, and the two goods are substitutes in consumption. Consumption goods in each country are denoted by q_{ic}^D. *Good 1* and *Good 2* are both tradable. Let P_1 and P_2, be the market prices of *Good 1* and *Good 2* respectively.

Let $U_c(q_{1c}^D, q_{2c}^D)$ be the utility function of the representative agent that consumes both goods in each country. U_c is a globally concave continuously differentiable function on an open, convex subset in $\mathbb{R}^2$. The marginal utilities are diminishing in *Good 1* and *Good 2*, that is, the utility of consuming one additional unit declines.

Consumers maximize their utility subject to their budget constraint or income $I_c = \sum_i (P_i q_{ic}^D)$, taking as given all market prices P_1 and P_2. Where I_c is income, and P_i is the price of good i. In the model, consumers owns the firms and receive rents of endowments, capital and labor. An alternative formulation of the model with the explicit solution for the consumer and producer problems is presented in the Appendix A yielding identical results for the cases presented in this chapter[1]. The first-order condition (FOC) equalizes the marginal rate of substitution to the price ratio, $\frac{\partial U_c/\partial q_{1c}^{*D}}{\partial U_c/\partial q_{2c}^{*D}} = \frac{P_1}{P_2}$. The solution guarantees that the critical points, q_{1c}^{*D} and q_{2c}^{*D}, represent the optimal solution to the consumer problem[2].

Countries are endowed with two production factors, capital and labor. The total capital in the economy is given by $\bar{K} = \sum_i \sum_c K_{ic}$, where K_{ic} is the capital

[1]See Appendix A for the analogous formulation of the consumer and producer problem
[2]See Theorem 21.6 and Theorem 21.7 of Simon and Blume (1994, p. 517)

used by sector *i* in country *c*. Capital is mobile across countries and as per the law of one price, the rent of capital is the same for both countries. Let r be the rent of capital for the economy. Let $\bar{L}_c$ be the endowment of labor for country *c*. Labor is a country specific production factor but is mobile between sectors. The resource constraint for labor is $\bar{L}_c = \sum_i L_{ic}$, where L_{ic} is the labor used by sector *i* in country *c*. Wages are specific for each country because of the immobility of labor across countries. Let w_c be the price of labor in country *c*. The input prices, w_c and r, clear the factor markets.

The production function of good *i* is defined as a function of capital and labor, $q_{ic} = q_{ic}(K_{ic}, L_{ic})$. The representative firm in sector *i* in country *c* maximizes profits, $P_i q_{ic} - w_c L_{ic} - rK_{ic}$, taking all prices as given. The marginal product of capital is given by the partial derivative of the profit function with respect to capital. The marginal product of labor is given by the partial derivative of the profit function with respect to labor.

The production of *Good 2* implies producing emissions, but the firms do not consider emissions as a production factor that they have to pay for. In this model, emissions are produced using production factors while producing *Good 2*. Both countries produce emissions exclusively when producing *Good 2*. Let $e_{2c} = e_{2c}(K_{2c}, L_{2c})$ represent the production function of emissions, defined as a function of the capital and labor in sector *2*. Thus, for different combinations of capital and labor it would be possible to get the same level of emissions. The total emissions in the economy is equal to $\sum_c e_{2c}$ and represents the amount of emissions produced by both countries when producing *Good 2*. *D* represents the marginal damage per unit of emissions, and the overall cost of pollution for the society is $D \cdot \sum_{c} e_{2c}(K_{2c}, L_{2c})$. *D* is assumed to be positive and the same for both countries.

Trade is determined by market equilibrium conditions, and because goods are tradable, trade will adjust to equalize the prices between countries. Let $\left(q_{ic} - q_{ic}^{D}\right)$ be the exports of good *i* in country *c*. If this is positive, it implies that country *c* is an exporter of Good *i*, and if it is negative, the country is an importer of Good *i*. Under these conditions, the balance of trade will determine the prices of goods. A market equilibrium condition states that the exports of good *i* in country *c* represents imports from the other country, such that $\sum_{c} q_{ic}^{D} = \sum_{c} q_{ic}(K_{ic},\ L_{ic})$. The market clearing condition, which equalizes supply to demand for each good across countries, implies that all production is consumed.

This Chapter's model has the objective to present a simplified version of the typical formulation of a general equilibrium model. The typical general equilibrium model would present the zero profit, market clearance, and income balance conditions. The zero-profit and market clearance are reflected in the capital, labor, and trade constraints in my model. The income balance condition establishes the factors from which households earn income. In this model, the households are the firms' owners and receive rents from capital and labor. This simplification aims to understand the workings of the policy in the simplest general equilibrium framework.

Equation (1) defines the overall welfare function for the global economy. W is the summation of the utilities of the representative agent for each country minus the damages of emissions from both countries.

$$W = \sum_c U_c\left(q_{1c}^D, q_{2c}^D\right) - D \cdot \sum_c e_{2c}(K_{2c}, L_{2c}) \qquad \forall c \tag{1}$$

In equation (1), *D* represents the marginal damage per unit of emissions, and the overall cost of pollution for the society is $D \cdot \sum_c e_{2c}(K_{2c}, L_{2c})$. *D* is assumed to be positive and the same for both countries[3].

Business as Usual

The business as usual scenario ignores regulations on emissions, and ignores the global damages caused by emissions to the environment. The business as usual (BAU) results are characterized by the solution to the following program:

$$\max_{q_{ic}^D, K_{ic}, L_{ic}} \sum_c U_c\left(q_{1c}^D, q_{2c}^D\right) \qquad \forall i, c \tag{2}$$

subject to i) the capital constraint $\bar{K} = \sum_c \sum_i K_{ic}$ and labor constraint $\bar{L}_c = \sum_i L_{ic}$ for each country *c*, and to ii) the production functions and trade conditions $\sum_c q_{ic}^D = \sum_c q_{ic}\left(K_{ic},\ L_{ic}\right)$ for each good *i*.

The first two constraints are the resource constraints for capital and labor, the trade condition $\sum_c q_{ic}^D = \sum_c q_{ic}(K_{ic},\ L_{ic})$ represents the trade constraint, and the supply and demand of *Good 1* and *Good 2* are equalized across countries, allowing countries to import the good with excess demand and to export the good with excess supply.

When solving the welfare maximization problem, maximization of equation (2) subject to the constraints yields the same results as solving the

[3]The overall welfare function ranks utility for the society. Equation (1) is an Arrow social welfare function, which aggregates across individual utilities and ranks overall welfare.

system of equations consisting of the FOCs for the consumer and producer problems described above. The multipliers (λ) represent the shadow values associated with a particular constraint in the welfare maximization problem. These shadow prices tell us what the optimal value of the objective function is in relation to a specific constraint and are likely to increase as a per unit increase in the resources of available capital and labor. λ_K is the multiplier associated with the capital constraint, and is equivalent to the rent of capital. λ_{L_c} is the multiplier associated with the labor constraint, and is equivalent to wages in country c. λ_{q_i} is the multiplier associated to the trade constraint, and is equivalent to the prices of *Good 1* and *Good 2*.

The solution of equation (2) is given by the FOCs of the maximization problem. Taking the derivatives of (2) and setting equal to zero with respect to q_{ic}^D, K_{ic}, L_{ic} yields the following FOCs:

The marginal utility is equal to the shadow price for both goods.

$$\frac{\partial U_c}{\partial q_{ic}^D} = \lambda_{q_i} \qquad \forall i, c \tag{3}$$

The marginal products of capital and labor are equal to the relative shadow factor prices in terms of the shadow price of *Good 1* and *Good 2*, respectively.

$$\frac{\partial q_{ic}\left(K_{ic},\ L_{ic}\right)}{\partial K_{ic}} = \frac{\lambda_K}{\lambda_{q_i}} \qquad \forall i, c \tag{4}$$

$$\frac{\partial q_{ic}\left(K_{ic},\ L_{ic}\right)}{\partial L_{ic}} = \frac{\lambda_{L_c}}{\lambda_{q_i}} \qquad \forall i, c \tag{5}$$

Using equation (3), I get the Marginal Rate of Substitution (MRS) of *Good 2* for *Good 1*.

$$\frac{\partial U_c / \partial q_{1c}^D}{\partial U_c / \partial q_{2c}^D} = \frac{\lambda_{q_1}}{\lambda_{q_2}} \qquad \forall c \tag{6}$$

Combining equations (4) and (5), I get the Marginal Rate of Transformation of labor for capital, which is equal to their relative shadow prices.

$$\frac{\partial q_{ic}\left(K_{ic}, L_{ic}\right) / \partial K_{ic}}{\partial q_{ic}\left(K_{ic}, L_{ic}\right) / \partial L_{ic}} = \frac{\lambda_K}{\lambda_{L_c}} \qquad \forall i, c \tag{7}$$

Lemma 1 *The BAU equilibrium is characterized by the optimization in equation* (2).

Proof - Lemma 1 (See Appendix A)

Social Optimum - "First Best"

A first best regulatory policy can improve overall welfare; however, the optimum conditions are not always satisfied in an economic model. For instance, there may be cases were a standard competitive equilibrium model is not guaranteed because one of the conditions for achieving such an equilibrium is infeasible. For example, output prices might not be equal to the marginal cost of the firms, or the ratio of prices between two goods may not be equal to each consumer's marginal rate of substitution between goods, or markets do not clear. Thus, when the optimum is not satisfied for whatever reason, even lack of coordination between agents or the presence of environmental externalities, all other equilibrium conditions will change such that the equilibrium is altered. This ability to account for all potential changes is an advantage of analyzing policies in a general equilibrium setting.

The social optimum is defined by the solution to the program

$$\max_{q_{ic}^D,\ L_{ic},\ K_{ic}} \sum_c U_c\left(q_{1c}^D, q_{2c}^D\right) - \sum_c D \cdot \left(e_{2c}\left(K_{2c},\ L_{2c}\right)\right) \qquad \forall c \tag{8}$$

subject to i) the capital constraint $\bar{K} = \sum_c \sum_i K_{ic}$ and labor constraint $\bar{L}_c = \sum_i L_{ic}$ for each country *c*, and ii) the production functions and trade conditions $\sum_c q_{ic}^D = \sum_c q_{ic}(K_{ic},\ L_{ic})$ for each good *i*. Note that equation (8) is different than equation (2) because emissions damages are subtracted from overall welfare.

The FOCs for q_{ic}^D are shown in equation (6) for both goods and are also valid here. Equation (7) for q_{ic} is valid for *Good 1*, but for *Good 2*, the FOCs of the first best program will change with respect to the BAU case. Equations (4) and (5) for *Good 2* now become:

$$\frac{\partial q_{2c}\left(K_{2c},L_{2c}\right)}{\partial K_{2c}}=\frac{\lambda_K}{\lambda_{q_2}}+\frac{\boldsymbol{D}}{\lambda_{q_2}}\frac{\partial e_2\left(K_{2c},L_{2c}\right)}{\partial K_{2c}}\qquad\forall c\tag{9}$$

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial L_{2c}}=\frac{\lambda_{L_c}}{\lambda_{q_2}}+\frac{\boldsymbol{D}}{\lambda_{q_2}}\frac{\partial e_2\left(K_{2c},L_{2c}\right)}{\partial L_{2c}}\qquad\forall c.\tag{10}$$

When combining the previous FOCs, equation (6) and equation (7) remain unaltered for *Good 1*. Equation (6) will remain for *Good 2*, but the Marginal Rate of Transformation of labor and capital for *Good 2*, equation (7), will change to:

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)/\partial K_{2c}}{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)/\partial L_{2c}}=\frac{\lambda_K+\boldsymbol{D}\left(\partial e_{2c}\left(K_{2c},\ L_{2c}\right)/\partial K_{2c}\right)}{\lambda_{L_c}+\boldsymbol{D}\left(\partial e_{2c}\left(K_{2c},\ L_{2c}\right)/\partial L_{2c}\right)}\qquad\forall c.\tag{11}$$

Proposition 1 *The business as usual scenario is not the first best.*

Proof - The overall welfare of the BAU case is smaller than the overall welfare of the first best case. Production, consumption, factor utilization, and emissions are also different. The program described in equation (2) ignores the environmental damages represented in equation (8). See Table V.3 columns 2 and 3.

IV.2. Cap and Trade and Intensity Standards

In this section, I present harmonized and unilateral regulations. In the harmonized cases, both countries regulate emissions by applying a coordinated regulatory policy. In the unilateral case, both countries have different regulations of emissions; *Country A* regulates the quantity of emissions e_{2A}, but *Country B* does not regulate its quantity of emissions, e_{2B}. The cases in which environmental regulations will improve overall welfare are determined by the maximization of a combined welfare function while changing the policy variables (i.e., the sum of the welfare of *Country A* and *Country B*), subject to the factor constraints and an emissions policy constraint.

The policies to consider are a standard cap and trade mechanism and emissions intensity standards. A cap and trade mechanism is usually a preferred policy instrument to regulate environmental externalities, because the correct implementation of the cap can create a market for emissions and impose the correct price on a missing market. An intensity standard is a regulation which limits the amount of emissions per unit of output. Emissions intensity standards are a second-best policy because while they tax emissions, they also introduce an output subsidy. However, when there is market failure and leakage of emissions, intensity standard regulations could dominate the cap and trade mechanism because the output effects from cap and trade may be offset by leakage. With leakage, the production of the dirty good may increase total emissions (Fischer and Newell, 2008; Fullerton and Heutel, 2010; Holland, 2012).

A cap and trade mechanism is a regulation which limits the total amount of emissions. This is usually preferred as an environmental regulatory policy. It is important to note that a harmonized C&T regulation is capable of emulating the first best only for a single value of the cap. The social optimum in this model refers to the scenario where an international agreement is set by the countries, and the regulator chooses the cap in each country such that the net social benefits are maximized. A key aspect of the policy simulations in this exercise is that they are all optimized. Even though all values are optimized in terms of maximizing overall welfare, only one policy choice, the optimal one, achieves the first best. Even for the simple model proposed in this exercise, the coordination that a cap and trade mechanism requires to emulate the first best is substantial.

Harmonized Cap and Trade Equilibrium

Through an intervention, a second-best equilibrium can be attained[4], but the economy cannot be restored to its first best welfare status if the regulation is incomplete, that is, achieving a first best equilibrium requires the complete removal of the conditions under which a first best equilibrium is not feasible.

For example, in trade policy, the main criticism of second-best policies is that the policy choice is not set to achieve the first best economic optimum but the second-best optimum. This is because first best policies are set at the domestic level and are therefore not global policies. This applies to the case of environmental policies too. Local policies are easier to implement because they require less information and less coordination effort. Even when the conditions are pro-environment, global policies are much more difficult to implement as there is lack of coordination, and dynamics of the industry make it difficult or impossible for countries and industries to synchronize regulatory policies.

In this exercise, to show that a second-best policy can attain the first best outcome, I impose a cap on emissions for the production of the dirty good in both countries. This is the harmonized case when regulation is imposed identically in both countries. Companies could trade emissions at the price of permission permits. Thus, the harmonized C&T equilibria are defined as

[4] Environmental taxes set to the total damages of emissions can restore the first best equilibrium.

$$\max_{q_{ic}^D,,\ K_{ic},L_{ic}} \sum_c U_c(q_{1c}^D,\ q_{2c}^D) \qquad \forall c \tag{12}$$

subject to i) the capital constraint $\bar{K} = \sum_c \sum_i K_{ic}$ and labor constraint $\bar{L}_c = \sum_i L_{ic}$ for each country *c*, ii) the production functions and trade conditions $\sum_c q_{ic}^D = \sum_c q_{ic}(K_{ic},\ L_{ic})$, and iii) the policy constraint, $e_{2A}(K_{2A}, L_{2A}) + e_{2B}(K_{2B}, L_{2B}) \leq \bar{e}$. Thus, the total quantity of emissions that *Country A* and *Country B* can produce is restricted to $\bar{e}$. λ_e is the multiplier associated to the constraint of emissions, and λ_e is equivalent to the global *price* of emissions. Note that the program in equation (12) is different to the program in equation (8) because of the emissions constraint.

The solution to the harmonized C&T scenario is obtain by solving the Lagrangian function defined in equation (A7). The FOCs of K_{2c} and L_{2c} are as follows:

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial K_{2c}} = \frac{\lambda_K}{\lambda_{q_2}} + \frac{\lambda_e}{\lambda_{q_2}} \frac{\partial e_2\left(K_{2c},\ L_{2c}\right)}{\partial K_{2c}} \qquad \forall c \tag{13}$$

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial L_{2c}} = \frac{\lambda_{L_c}}{\lambda_{q_2}} + \frac{\lambda_e}{\lambda_{q_2}} \frac{\partial e_2\left(K_{2c},\ L_{2c}\right)}{\partial L_{2c}} \qquad \forall c \tag{14}$$

Similar to the previous case, equations (6) and (7) are valid for *Good 1*. When combining the previous FOCs, equation (6) remains unaltered for *Good 2*, but the Marginal Rate of Transformation of labor and capital for *Good 2*, equation (7), will change to:

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)/\partial K_{2c}}{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)/\partial L_{2c}} = \frac{\lambda_K + \lambda_e\left(\partial e_{2c}\left(K_{2c},\ L_{2c}\right)/\partial K_{2c}\right)}{\lambda_{L_c} + \lambda_e\left(\partial e_{2c}\left(K_{2c},\ L_{2c}\right)/\partial L_{2c}\right)} \qquad \forall c. \tag{15}$$

If the cap is set such that λ_e is equivalent to *D*, then the FOCs in equation (15) are equivalent to the FOCs in equation (11).

Lemma 2 *The harmonized C&T equilibrium is characterized by the optimization in equation* (12).

Proof - Lemma 2 (See Appendix A)

Unilateral Cap and Trade Equilibrium

The unilateral case in the theoretical model assumes that only *Country A* regulates emissions, while *Country B* does not. A second-best unilateral policy consists in setting a cap on emissions unilaterally, on the production of the dirty good in the country that decides to regulate. Thus, the unilateral C&T equilibria are defined as

$$\max_{q_{ic}^D,,\ K_{ic},L_{ic}} \sum_c U_c(q_{1c}^D,\ q_{2c}^D) \qquad \forall c \tag{16}$$

subject to i) the capital constraint $\bar{K} = \sum\limits_c \sum\limits_i K_{ic}$ and labor constraint $\bar{L}_c = \sum\limits_i L_{ic}$ for each country *c*, ii) the production functions and trade conditions $\sum\limits_c q_{ic}^D = \sum\limits_c q_{ic}(K_{ic},\ L_{ic})$, and iii) the policy constraint, $e_{2A}(K_{2A}, L_{2A}) \leq \bar{e}_{2A}$. In this case, the total quantity of emissions that *Country A* can produce is restricted to $\bar{e}_{2A}$. λ_{e_A} is the multiplier associated with the emissions constraint for *Country A*, and λ_{e_A} is equivalent to an implicit *price* on emissions for *Country A*. Note that the program in equation (16) is different to the program in equation (12) because of the emissions constraint.

The FOC of the maximization problem for *Country B* is the same as equations (6) and (7) for the BAU case. For *Country A* that regulates emissions, the main difference is the derivative with respect to K_{2A} and L_{2A} of the production function of *Good 2*. The FOCs of K_{2A} and L_{2A} are as follows:

$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial K_{2A}} = \frac{\lambda_K}{\lambda_{q_2}} + \frac{\lambda_{e_A}}{\lambda_{q_2}}\frac{\partial e_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial K_{2A}} \tag{17}$$

$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial L_{2A}} = \frac{\lambda_{L_A}}{\lambda_{q_2}} + \frac{\lambda_{e_A}}{\lambda_{q_2}}\frac{\partial e_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial L_{2A}} \tag{18}$$

The Marginal Rate of Transformation of labor and capital for *Good 2*, equation (7), will change to:

$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)/\partial K_{2A}}{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)/\partial L_{2A}} = \frac{\lambda_K + \lambda_{e_A}\left(\partial e_{2A}\left(K_{2A},\ L_{2A}\right)/\partial K_{2A}\right)}{\lambda_{L_A} + \lambda_{e_A}\left(\partial e_{2A}\left(K_{2A},\ L_{2A}\right)/\partial L_{2A}\right)}. \tag{19}$$

Lemma 3 *The unilateral C&T equilibrium is characterized by the optimization in equation* (16).

Proof - Lemma 3 (See Appendix A)

Cap and Trade and First Best

If all countries regulate emissions and emissions are set to the optimal level for each country, then the C&T mechanism can be the first best policy. However, for global policies, the C&T mechanism is not guaranteed to be the first best policy. For instance, if a constraint of emissions is defined as $\sum_c e_c(K_{2c},\ L_{2c}) \leq \sum_c \bar{e}_c$ where $\sum_c \bar{e}_c$ represents the total amount of emissions, and if the emissions cap is not set optimally, then the C&T mechanism will not be first best. In practice, calculating the optimal amount of emissions, e_c, per country can be extremely difficult. There are several factors to consider in the calculation. It is even more difficult for countries to pledge to reduce the correct amount of emissions to reach a global target.

The social optimum can be attained if both countries have caps such that the total damage of emissions is set to $\sum_c De_{2c}(K^*_{2c},\ L^*_{2c})$, where *Country A* and *Country B* choose capital and labor such that the global damage of emissions is set to the optimal overall target. The social optimum is described in equations (8) to (11). The values of K^*_{2c} and L^*_{2c} are the solutions to the program above. The optimal cap is set equal to the damage function of emissions evaluated at the optimal values of capital and labor, and thus the total damage of emissions is $\sum_c D_c e_c(K^*_{2c},\ L^*_{2c})$.

Proposition 2 *The harmonized C&T equilibrium can attain the first best outcome. The unilateral C&T equilibrium cannot attain the first best outcome due to leakage.*

Proof - Proposition 2 (See Figure V.1 and analytical proof in Appendix A)

Harmonized Intensity Standards Equilibrium

In the case of intensity standards, the objective function is the same as that in the C&T case but has a different constraint on emissions determined by IS. The harmonized intensity standard (IS) equilibrium is characterized by the following solution to the program:

$$\max_{q_{ic}^{D},\ K_{ic}, L_{ic}} \sum_{c} U_c\left(q_{1c}^{D},\ q_{2c}^{D}\right) \qquad \forall c \tag{20}$$

subject to i) the capital constraint $\bar{K} = \sum_{c}\sum_{i} K_{ic}$ and labor constraint $\bar{L}_c = \sum_{i} L_{ic}$ for each country *c*, ii) the production functions and trade conditions $\sum_{c} q_{ic}^{D} = \sum_{c} q_{ic}(K_{ic},\ L_{ic})$, and iii) the policy constraint, $\frac{e_{2A}+e_{2B}}{q_{2A}+q_{2B}} \leq IS$. The IS constraint represents the ratio of total emissions associated with the total production of *Good 2*. The smaller the IS, the smaller the emissions produced from the production of *Good 2*. Note that the program in equation (20) is different to the program in equation (16) because of the emissions constraint.

λ_{IS} is the multiplier associated with the IS constraint of emissions. The FOC of the consumer maximization problem for *Country A* and *Country B* are the same as equation (6). The main difference is the inclusion of partial derivatives of the production function of *Good 2*, with respect to K_{2c} and with respect to L_{2c}, shown as follows:

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial K_{2c}} = \frac{1}{\left(\lambda_{q_2} + \lambda_{IS} IS\right)}\left(\lambda_K + \lambda_{IS}\frac{\partial e_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial K_{2c}}\right) \qquad \forall c \tag{21}$$

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial L_{2c}} = \frac{1}{\left(\lambda_{q_2} + \lambda_{IS} IS\right)}\left(\lambda_{L_c} + \lambda_{IS}\frac{\partial e_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial L_{2c}}\right) \qquad \forall c \tag{22}$$

When combining the previous FOCs, equation (6) remains unaltered, but the Marginal Rate of Transformation of labor and capital for *Good 2* is similar to equation (15):

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)/\partial K_{2c}}{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)/\partial L_{2c}} = \frac{\lambda_K + \lambda_{IS}\left(\partial e_{2c}\left(K_{2c},\ L_{2c}\right)/\partial K_{2c}\right)}{\lambda_{L_c} + \lambda_{IS}\left(\partial e_{2c}\left(K_{2c},\ L_{2c}\right)/\partial L_{2c}\right)} \qquad \forall c. \tag{23}$$

The main difference between equation (23) and equation (15) is the multiplier on the constraint λ_{IS}. Only if the shadow price of emissions λ_{IS}, is equal to the shadow price of emissions, λ_e, will the IS replicate the first best. If λ_{IS} is equal to D, then equation (23) is the same as equation (11). In that case, equation (21) and equation (22) are not the same as equation (9) and equation (10) because λ_{IS} is not equal than zero. By construction, this case will not be possible since the constraint on emissions is always different for both cases, even when assuming symmetry. The C&T case constraint applies to total emissions in the program of equation (12), whereas the constraint of the IS applies to total emissions relative to total production of *Good 2* in the program for equation (20), and therefore the shadow prices of emissions are not equal. However they will be equal when the total output of the BAU case and the total production of *Good 2* are equal.

Lemma 4 *The harmonized IS equilibrium is characterized by the optimization shown in* (20).

Proof - Lemma 4 (See Appendix A)

Unilateral Intensity Standards Equilibrium

The unilateral intensity standards (IS) equilibrium is characterized by the solution to the following program:

$$\max_{q_{ic}^{D},\ K_{ic}, L_{ic}} \sum_{c} U_c \left(q_{1c}^{D},\ q_{2c}^{D}\right) \qquad \forall c \tag{24}$$

subject to i) the capital constraint $\bar{K} = \sum_{c} \sum_{i} K_{ic}$ and labor constraint $\bar{L}_c = \sum_{i} L_{ic}$ for each country *c*, ii) the production functions and trade conditions $\sum_{c} q_{ic}^{D} = \sum_{c} q_{ic}(K_{ic},\ L_{ic})$, and iii) the policy constraints $\frac{e_{2A}(K_{2A},\ L_{2A})}{q_{2A}(K_{2A}, L_{2A})} \leq IS_{2A}$. λ_{IS_A} is the multiplier associated with the IS constraint of emissions only for *Country A*. Recall that *Country B* does not regulate emissions in the unilateral cases. The FOC of the consumer maximization problem for *Country A* and *Country B* are the same as equation (6). The program in equation (24) is different to the program in equations (12), (16), and (20) because of the emissions constraint.

The fundamental difference in the cases above is the constraint on emissions. In the present case, the shadow price of emissions is determined by the multiplier λ_{IS_A}. The price of emissions for the unilateral IS case will be similar to the price of emissions in the harmonized IS case, only if emissions for the production of *Good 2* in *Country B* are close to zero or negligible in affecting the price.

The FOCs of the maximization problem for *Country A* are the same as equations (2) to (9). The main difference is in the derivatives of the production function of *Good 2* in *Country A* with respect to K_{2A} and with respect to L_{2A}, as follows:

$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial K_{2A}} = \frac{1}{\left(\lambda_{q_2} + \lambda_{IS_A} IS_A\right)}\left(\lambda_K + \lambda_{IS_A}\frac{\partial e_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial K_{2A}}\right) \tag{25}$$

$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial L_{2A}} = \frac{1}{\left(\lambda_{q_2} + \lambda_{IS_A} IS_A\right)}\left(\lambda_{L_A} + \lambda_{IS_A}\frac{\partial e_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial L_{2A}}\right) \tag{26}$$

When combining the previous FOCs, equation (6) remains unaltered, but the Marginal Rate of Transformation of labor and capital for *Good 2* is similar to equation (19).

$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)/\partial K_{2A}}{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)/\partial L_{2A}} = \frac{\lambda_K + \lambda_{IS_A}\left(\partial e_{2A}\left(K_{2A},\ L_{2A}\right)/\partial K_{2A}\right)}{\lambda_{L_A} + \lambda_{IS_A}\left(\partial e_{2A}\left(K_{2A},\ L_{2A}\right)/\partial L_{2A}\right)} \tag{27}$$

The main difference between equation (27) and equation (19) is the multiplier on the constraint λ_{IS_A}. Similar to the previous cases, the shadow price of emissions, λ_{IS_A}, is the fundamental difference between the present case and the cases presented above.

Lemma 5 *The unilateral IS equilibrium is characterized by the optimization shown in* (23).

Proof - Lemma 5 (See Appendix A)

Intensity Standards and First Best

In the real world, second-best policies are implemented through alternative approaches. For example, federal programs in the United States set

Renewable Fuel Standards in an attempt to incorporate renewable fuels in the transportation sector fuel mix through annual volume obligations. Such obligations constrain the percentage use of fossil fuels in relation to the total amount of fuel used in the transportation sector.

The second-best unilateral intensity standard policy used here will set the percentage of emissions per output that can be produced by the dirty good in *Country A*. The main difference between the C&T and the IS regulatory instruments, is that the cap can attain the first best when it is set optimally. The IS will not attain the first best, but it may be a preferred regulatory instrument under unilateral regulation mainly because it does better for relatively smaller percentages of emissions reductions. In Chapter V, I show that an IS regulation can reduce an equal amount of emissions as a C&T regulation can, and an IS regulation does better in terms of overall welfare.

Proposition 3 *The harmonized IS equilibrium and the unilateral IS equilibrium cannot attain first best.*

Proof - Proposition 3 (See Figure V.1 and the analytical proof in Appendix A)

A solution for the above programs is not generalized. Besides the fact that the theoretical properties of the utility and production functions should hold, the program works best for utility functions that meet the condition of additive separability, so that welfare across countries can be aggregated and maximized. The optimization of the previous model will rely on the mathematical properties of the overall welfare function and the parameters chosen for calibration.

Proposition 4 *If* $\sum_c U_c(q_{1c}^D,\ q_{2c}^D)$ *is globally concave, then an equilibrium allocation exists for BAU, CAT, and IS. If strictly, then unique.*

Proof - Proposition 4 (See Appendix A)

IV.3. Which Policies are Optimal under Incomplete Regulation and Leakage?

It is not straightforward to understand what policies are the best when incomplete regulation and leakage exist, since I cannot provide an analytical solution even with the simplest analytical model. Thus, the use of numerical optimization is useful in this regard. In the next chapter, with the help of a numerical exercise, I present the optimal values of the C&T and IS policies, in both the harmonized and the unilateral cases, to compare maximum welfare across scenarios (See Table V.7). I explore all cases when overall welfare is maximized to learn under what circumstances the second-best policies are optimal and report the maximum welfare.

Proposition 5 *Under incomplete regulation and leakage, the IS regulation is capable of dominating the C&T regulation.*

Proof - Proposition 5 (See Table V.7 in Chapter V)

IV.4. Conclusion

In this chapter, I compared two environmental regulations and their effects in terms of maximizing overall welfare. A policy when both countries regulate emissions is always preferred in terms of maximizing overall welfare. If the two countries coordinate on a policy to reduce emissions, the harmonization of policies can lead to welfare improvements over unilateral policies, regardless of whether the countries use cap and trade or intensity standards as the regulatory mechanism. The case of no regulation sees the smallest aggregate welfare as compared with harmonized policies or complete regulation. It is possible to explore the practicability of this conclusion with the help of a numerical simulation.

More importantly, if the two countries implement a cap and trade mechanism and choose the cap as being equal to the marginal damage of emissions, the economy can reach the first best outcome. However, it is not sufficient that the values are optimized, and it is very important to note that the cap and trade mechanism has to be set at the ‘right’ level to attain the first best. The cap and trade mechanism can attain the first best only for a single value of the policy. The advantage of using a simple model such as the one presented in this chapter is that it helps to make clear that the implementation of a cap and trade mechanism will not necessarily achieve the first best and may be a sub-optimal instrument when the policy is not set to capture the full marginal damage. Furthermore, it highlights the importance of coordination across countries and sectors to implement successful policies.

CHAPTER V

MODEL CALIBRATION AND RESULTS

The objective of this chapter is to present the results of a numerical exercise that support the model proposed in the previous chapter. First, section V.1 presents the calibration of the model, the main assumptions about functional forms for the equations, and the values of the parameters. Then, section V.2 presents the results of the numerical simulations. Section V.3 presents the comparison across cases, and section V.4 presents the sensitivity analysis. Finally, I present the conclusions.

V.1. Model Calibration

In the model in Chapter IV, for each endogenous variable in the model, there is an associated equation that represents an equilibrium condition. The equations are grouped by demand, production, capital and labor, and trade equations. Table V.1 presents the functional forms and their corresponding variables in the system.

The preferred functional form for all cases is the Constant Elasticity of Substitution (CES) function. The CES function is characterized by additive separability across goods and production factors, which makes it possible to solve the system. The CES specification is also general enough to allow for the calibration of more specific values for the elasticity of substitution, such as for the Cobb Douglas and Leontief functions.

The parameters for calibration were chosen to guarantee that the system

Table V.1. Equations of the Model

Description (Defining Variable)	**Functional Form**
Overall Welfare Function	$W = U_A + U_B - D \cdot \sum_c e_{2c}(K_{2c}, L_{2c})$
Utility Functions (q_{ic}^D)	$U_c = \left(\alpha_c \left(q_{1c}^D\right)^{\rho_c} + (1-\alpha_c)\left(q_{2c}^D\right)^{\rho_c}\right)^{\frac{\theta_c}{\rho_c}}$
Production Functions (q_{ic})	$q_{ic} = \gamma_c \left[\beta_c K_{ic}^{\phi_c} + (1-\beta_c)\, L_{ic}^{\phi_c}\right]^{\theta_c/\phi_c}$
Capital Constraint (K_{ic})	$\bar{K} = \sum_c \sum_i K_{ic}$
Labor Constraints (L_{ic})	$\bar{L}_c = \sum_i L_{ic}$
Trade Constraint	$\sum_c q_{ic}^D = \sum_c q_{ic}(K_{ic},\ L_{ic})$
Emissions Function (e_{2c})	$e_{2c} = \left[\mu_{2c} K_{2c}^{\delta_{2c}} + (1-\mu_{2c}) L_{2c}^{\delta_{2c}}\right]^{\theta_c/\delta_{2c}}$
Case Specific Regulatory Constraints	
Harmonized Cap and Trade	$e_{2A}(K_{2A}, L_{2A}) + e_{2B}(K_{2B}, L_{2B}) \leq \bar{e}_2$
Harmonized Intensity Standard	$\frac{e_{2A}+e_{2B}}{q_{2A}+q_{2B}} \leq IS$
Unilateral Cap and Trade	$e_{2A}(K_{2A}, L_{2A}) \leq \bar{e}_{2A}$
Unilateral Intensity Standard	$\frac{e_{2A}}{q_{2A}} \leq IS_A$

encounters a feasible solution. Although the model was built to allow for different parameters across countries and goods, the parametrization was done to compare the effects of the environmental regulations in two identical countries. The selection of parameters for the baseline is presented in Table V.2.

Table V.2. Parameters and Equations of the Model

Parameter	Description	Value
Utility function		
α_c	Weight of *Good 1*	0.50
ρ_c	Elasticity of substitution parameter	0.25
Production		
γ_c	Technology parameter	0.85
β_c	Weight of capital in the production of goods	0.30
ϕ_c	Elasticity of substitution parameter	0.60
Emissions		
μ_{2c}	Weight of capital in the production of emissions	0.45
δ_{2c}	Elasticity of substitution parameter	0.90
D	Marginal damage per unit of emissions	0.30
Returns to scale		
θ_c	Returns to scale parameter	0.99
$\bar{L}_c$	Endowment of labor in country c	50.00
$\bar{K}$	Total capital in the economy	200.00

V.2. Results of the Numerical Simulations

This section contains the results of the numerical exercise that allow us to check the hypotheses presented in the previous chapter. These results are presented in Table V.3 to Table V.6. Each table presents the effects of a specific regulatory scenario and the effects of the regulation on the main variables are discussed.

The solution to the model requires solving the optimization problem described in the previous chapter. The welfare maximization problem is equivalent to solving a system of numerical equations, which in a typical general equilibrium formulation.

The results of the numerical simulations are presented in Table V.3 through Table V.7. For this exercise, symmetry between countries is assumed, that is, *Country A* and *Country B* have the same parameters[1].

When there is no regulation, both countries *A* and *B* produce as much

[1] It is straightforward to rely on the symmetry assumption.

emission as they need to maximize their profits and utility. This scenario is referred to as Business as Usual (BAU). Firms could obtain higher profits from the utilization of inputs in countries that set no regulations or do not have strict regulations on emissions. Because emissions are considered a 'free' variable with its associated production function, the resulting value of the BAU case's emissions was stored to apply the later cases of regulatory policies.

Harmonized C&T

Table V.3 presents the results of the harmonized C&T scenario. The upper part of Table V.3 presents the results for *Country A* and the bottom part presents the results for *Country B*. The first column contains a description of the variables, the second column shows the first best results, and the third column shows the results of the BAU case. Under BAU and under harmonized regulation, *Country A* and *Country B* are identical and they will have identical outcomes. Outcomes only differ in the cases of unilateral regulations where the countries are regulated differently. The remaining columns correspond to the harmonized C&T scenario for different percentages of global emissions reductions in the production of *Good 2* (See policy parameter $\bar{e}_2$ listed in the last row of Table V.3).

Overall welfare is maximized in the first best case and the lowest welfare corresponds to the BAU scenario. As the cap tightens, overall welfare increases up to certain level and then starts to decrease (See Figure V.1). In this model and with the proposed parameters, maximum welfare is obtained with a larger percentage of global emissions reductions relative to other cases. It is important to note that the harmonized C&T case is capable of replicating the results of the first best, but only for one value of the percentage of emissions reductions. As it is represented in Table V.3, this value corresponds to 75%; the other values of the policy parameter will return optimized solutions, but they do not achieve the first best.

In the harmonized C&T case, the production of the clean good, *Good 1* (q_1), increases in both countries with the stringency of the cap and trade mechanism. The production of the dirty good, *Good 2* (q_2), decreases in both countries as the cap tightens. This is because *Good 1* is a substitute for *Good 2*, and so the cap represents an implicit tax on the production of the dirty good.

To produce more of the clean good, both countries use more capital and less labor. Labor is relatively expensive in relation to capital in the production of the clean good. The relative factor prices or the wage to rent ratio increases. The marginal productivity of capital decreases, whereas the marginal productivity of labor increases. The converse is true for the production of the dirty good. Labor shifts to the production of the dirty good, *Good 2*, causing the capital-labor ratio to become smaller as the cap tightens. Wages are lower in the production of the dirty good and the marginal productivity of capital increase relative to labor.

Overall, the harmonized C&T regulation has the effect of decreasing consumption of the good that is regulated. As the cap tightens, the consumption of *Good 2* decreases relative to *Good 1*, whereas the demand of the clean good, *Good 1*, increases in both countries.

The assumption of the model is that only the production of *Good 2* is associated with the production of emissions. Emissions are produced by using capital and labor in the production of *Good 2*. Because there is less production of *Good 2*, emissions decreases with the stringency of the cap (See Figure V.2).

Table V.3. Harmonized Cap and Trade: Countries A & B regulate emissions

	First Best	**BAU**[a.]	**Increasingly Stringent Policies**											
Welfare[b.] W	43.67	37.86	38.48	39.07	40.17	41.16	42.02	42.74	43.29	43.62	**43.67**	43.61	42.97	41.93
Total damages[c.]	3.14	12.64	12.01	11.38	10.12	8.85	7.59	6.32	5.06	3.79	**3.14**	2.53	1.26	0.63
Policy[d.]			1%	10%	20%	30%	40%	50%	60%	70%	**74%**	80%	90%	95%
Country A														
Utility U_A	23.40	25.25	25.25	25.23	25.14	25.00	24.80	24.53	24.17	23.70	**23.40**	23.07	22.12	21.28
Production q_{1A}	30.11	26.09	26.44	26.78	27.42	28.03	28.59	29.10	29.56	29.94	**30.11**	30.24	30.35	30.25
Production q_{2A}	19.14	26.09	25.73	25.36	24.59	23.77	22.89	21.95	20.93	19.79	**19.14**	18.47	16.78	15.48
Capital K_{1A}	89.53	50.00	52.65	55.30	60.60	65.88	71.15	76.41	81.64	86.84	**89.53**	92.00	97.04	99.43
Capital K_{2A}	10.47	50.00	47.35	44.70	39.40	34.12	28.85	23.59	18.36	13.16	**10.57**	8.00	2.96	0.57
Labor L_{1A}	20.13	25.00	24.70	24.41	23.81	23.20	22.58	21.94	21.26	20.53	**20.13**	19.72	18.73	18.08
Labor L_{2A}	29.87	25.00	25.30	25.59	26.19	26.80	27.42	28.06	28.74	29.47	**29.87**	30.28	31.27	31.92
Consumption q_{1A}^D	30.11	26.09	26.44	26.78	27.42	28.03	28.59	29.10	29.56	29.94	**30.11**	30.24	30.35	30.25
Consumption q_{2A}^D	19.14	26.09	25.73	25.36	24.59	23.77	22.89	21.95	20.93	19.79	**19.14**	18.47	16.78	15.48
Emissions e_{2A}	5.23	21.07	20.02	18.97	16.86	14.75	12.64	10.54	8.43	6.32	**5.23**	4.21	2.11	1.05
Country B														
Utility U_B	23.40	25.25	25.25	25.23	25.14	25.00	24.80	24.53	24.17	23.71	**23.40**	23.07	22.12	21.28
Production q_{1B}	30.11	26.09	26.44	26.78	27.42	28.03	28.59	29.10	29.56	29.94	**30.11**	30.24	30.35	30.25
Production q_{2B}	19.14	26.09	25.73	25.36	24.59	23.77	22.89	21.95	20.93	19.79	**19.14**	18.47	16.78	15.48
Capital K_{1B}	89.53	50.00	52.65	55.30	60.60	65.88	71.15	76.41	81.64	86.84	**89.53**	92.00	97.04	99.43
Capital K_{2B}	10.47	50.00	47.35	44.70	39.40	34.12	28.85	23.59	18.36	13.16	**10.47**	8.00	2.96	0.57
Labor L_{1B}	20.13	25.00	24.70	24.41	23.81	23.20	22.58	21.94	21.26	20.53	**20.13**	19.72	18.73	18.08
Labor L_{2A}	29.87	25.00	25.30	25.59	26.19	26.80	27.42	28.06	28.74	29.47	**29.87**	30.28	31.27	31.92
Consumption q_{1B}^D	30.11	26.09	26.44	26.78	27.42	28.03	28.59	29.10	29.56	29.94	**30.11**	30.24	30.35	30.25
Consumption q_{2B}^D	19.14	26.09	25.73	25.36	24.59	23.77	22.89	21.95	20.93	19.79	**19.14**	18.48	16.78	15.48
Emissions e_{2B}	5.23	21.07	20.02	18.97	16.86	14.75	12.64	10.54	8.43	6.32	**5.23**	4.21	2.11	1.05

a. BAU - Business as Usual scenario. The values of the parameters for the calibration of the BAU are in Table V.2.
b. $W = U_A + U_B - D \cdot \sum_c e_{2c}$.
c. The marginal damage of emissions is $D = 0.3$, which is the same value for both countries.
d. Policy refers to the % of emissions reductions with respect to the BAU scenario of both countries.
Emissions reductions are calculated as $\bar{e}_2 = (1 - \%reduction) * \sum_c e_{2c}^{BAU}$.

Unilateral C&T

Table V.4 presents the case of unilateral C&T regulation. Only *Country A* regulates emissions by imposing a cap on the production of the dirty good, *Good 2*. The first best is not attained when applying a C&T unilateral regulation.

The results are not symmetric. The production of *Good 1* increases in *Country A* and decreases in *Country B*. The country that does not regulate emissions increases the production of the dirty good, *Good 2*, and significantly decreases the production of the clean good, *Good 1*.

To produce more of the clean good, *Country A* will use more capital and more labor. The utilization of capital and labor in the production of the clean good will increase in *Country A*, and the utilization of capital and labor will increase in the production of the dirty good in *Country B*.

The unilateral C&T regulation has the effect of decreasing consumption of the dirty good that is regulated only in the country that regulates it, *Country A*. As the cap tightens, consumption of *Good 1* increases relative to *Good 2* in *Country A*. Consumption of *Good 1* relative to *Good 2* decreases in *Country B*. The demand for the clean good increases only in *Country A*.

Emissions will decrease only in *Country A* and emissions will increase in *Country B*.

Harmonized IS

In the harmonized IS case the regulatory mechanism reduces emissions through both substitution and output effects. The substitution effect reduces emissions by employing additional inputs (capital or labor, depending on which is cheaper). The output effect reduces emissions by reducing the consumption of the polluting good.

Table V.5 presents the case where both countries reduce emissions by imposing standards in the production of the dirty good, *Good 2*. The regulation targets the ratio of total global emissions of *Good 2* as per the total global production of *Good 2*. The higher the policy parameter (IS), the smaller the ratio of emissions generated in the production of *Good 2*.

Table V.5 has the same format as Table V.3. The results show that overall welfare increases as the regulation approaches to a ratio of one-third of emissions reductions per output of *Good 2*, relative to the BAU case, after which

Table V.4. Unilateral Cap and Trade: Country A regulates emissions

	First Best	**BAU**[a.]	**Increasingly Stringent Policies**											
Welfare[b.] W	43.67	37.86	37.88	37.91	37.94	37.96	**37.98**	37.97	37.95	37.93	37.87	37.80	37.68	37.61
Total damages[c.]	3.14	12.64	12.62	12.60	12.55	12.52	**12.50**	12.50	12.49	12.49	12.50	12.53	12.58	12.61
Policy[d.]			1%	10%	20%	30%	**38%**	40%	50%	60%	70%	80%	90%	95%
Country A														
Utility U_A	23.40	25.25	25.25	25.25	25.25	25.24	**25.23**	25.23	25.22	25.21	25.19	25.16	25.13	25.11
Production q_{1A}	30.11	26.09	27.21	28.34	30.63	32.97	**34.89**	35.37	37.82	40.33	42.91	45.59	48.37	49.78
Production q_{2A}	19.14	26.09	24.88	23.66	21.20	18.69	**16.66**	16.15	13.55	10.89	8.16	5.33	2.36	0.83
Capital K_{1A}	89.53	50.00	52.19	54.41	58.87	63.40	**67.05**	67.97	72.58	77.21	81.84	86.42	90.81	92.76
Capital K_{2A}	10.47	50.00	47.36	44.73	39.46	34.22	**30.03**	28.98	23.77	18.59	13.45	8.37	3.43	1.13
Labor L_{1A}	20.13	25.00	26.07	27.16	29.38	31.66	**33.53**	34.00	36.43	38.95	41.59	44.40	47.44	49.09
Labor L_{2A}	29.87	25.00	23.93	22.84	20.62	18.34	**16.47**	16.00	13.57	11.05	8.41	5.60	2.56	0.91
Consumption q^D_{1A}	30.11	26.09	27.21	28.34	30.63	32.97	**34.89**	35.37	37.82	40.33	42.91	45.59	48.37	49.78
Consumption q^D_{2A}	19.14	26.09	26.07	26.06	26.02	25.98	**25.95**	25.94	25.89	25.83	25.76	25.67	25.54	25.46
Emissions e_{2A}	5.23	21.07	20.02	18.97	16.86	14.75	**13.07**	12.64	10.54	8.43	6.32	4.21	2.11	1.05
Country B														
Utility U_B	23.40	25.25	25.25	25.25	25.25	25.24	**25.23**	25.23	25.22	25.21	25.19	25.16	25.13	25.11
Production q_{1B}	30.11	26.09	25.00	23.90	21.66	19.37	**17.50**	17.03	14.63	12.18	9.66	7.06	4.40	3.08
Production q_{2B}	19.14	26.09	27.27	28.45	30.85	33.27	**35.24**	35.73	38.23	40.77	43.36	46.01	48.72	50.08
Capital K_{1B}	89.53	50.00	48.02	46.00	41.85	37.55	**33.99**	33.09	28.49	23.74	18.84	13.77	8.57	5.98
Capital K_{2B}	10.47	50.00	52.42	54.86	59.81	64.84	**68.92**	69.95	75.16	80.46	85.88	91.44	97.19	100.12
Labor L_{1B}	20.13	25.00	23.90	22.80	20.58	18.34	**16.52**	16.06	13.74	11.39	8.99	6.54	4.05	2.82
Labor L_{2A}	29.87	25.00	26.10	27.20	29.42	31.66	**33.48**	33.94	36.26	38.61	41.01	43.46	45.95	47.18
Consumption q^D_{1B}	30.11	26.09	25.00	23.90	21.66	19.37	**17.50**	17.03	14.63	12.18	9.66	7.06	4.40	3.08
Consumption q^D_{2B}	19.14	26.09	26.07	26.06	26.02	25.98	**25.95**	25.94	25.89	25.83	25.76	25.67	25.54	25.45
Emissions e_{2B}	5.23	21.07	22.04	23.02	24.99	26.99	**28.61**	29.02	31.09	33.19	35.34	37.54	39.81	40.97

a. The values of the parameters for the calibration of the BAU are in Table V.2.
b. $W = U_A + U_B - D \cdot \sum_c e_{2c}$.
c. The marginal damage of emissions is $D = 0.3$, which is the same value for both countries.
d. Policy refers to the % of emissions reductions with respect to the BAU scenario of *Country A*.
Emissions reductions are calculated as $\bar{e}_{2A} = (1 - \%reduction) * e^{BAU}_{2A}$.

overall welfare starts to decrease. It is important to note that the IS case will not replicate the results of the first best, not even at the highest value of welfare that can be attained with an IS regulatory policy (See Figure V.1).

In both countries, the production of the clean good will increase and the production of the dirty good will decrease when the regulation tightens up.

Both countries will use more capital and less labor in the production of the clean good, and less capital and more labor in the production of the dirty good. Although capital is mobile across countries, in the harmonized cases, there is a reallocation of the production factors across industries within each country.

As the ratio of emissions per output of *Good 2* decreases overall, the consumption of *Good 2* decreases, and the demand of the clean good, *Good 1*, increases in both countries.

Table V.5. Harmonized Intensity Standard: Countries A & B regulate emissions

	First Best	**BAU**[a.]	**Increasingly Stringent Policies**											
Welfare[b.] W	43.67	37.86	38.48	39.09	40.27	41.33	42.23	42.93	43.38	**43.54**	43.53	43.27	42.29	39.12
Total damages[c.]	3.14	12.64	12.01	11.34	9.93	8.48	7.02	5.59	4.24	**3.10**	2.98	1.83	0.83	0.47
Policy[d.]			1%	10%	20%	30%	40%	50%	60%	**69%**	70%	80%	90%	95%
Country A														
Utility U_A	23.40	25.25	25.24	25.22	25.10	24.91	24.62	24.26	23.81	**23.31**	23.25	22.55	21.56	19.80
Production q_{1A}	30.11	26.09	26.08	26.11	26.24	26.48	26.80	27.17	27.57	**27.94**	27.98	28.36	28.56	21.41
Production q_{2A}	19.14	26.09	26.08	25.99	25.62	24.99	24.13	23.07	21.85	**20.61**	20.47	18.90	17.03	19.43
Capital K_{1A}	89.53	50.00	52.69	55.49	61.38	67.47	73.56	79.47	85.05	**89.71**	90.21	94.82	98.74	100.00
Capital K_{2A}	10.47	50.00	47.31	44.51	38.62	32.53	26.44	20.53	14.95	**10.29**	9.79	5.18	1.26	0.00
Labor L_{1A}	20.13	25.00	24.13	23.31	21.79	20.47	19.36	18.43	17.68	**17.13**	17.07	16.58	16.01	7.33
Labor L_{2A}	29.87	25.00	25.87	26.69	28.21	29.53	30.64	31.57	32.32	**32.87**	32.93	33.42	33.99	42.67
Consumption q^D_{1A}	30.11	26.09	26.08	26.11	26.24	26.48	26.80	27.17	27.57	**27.94**	27.98	28.36	28.56	21.41
Consumption q^D_{2A}	19.14	26.09	26.08	25.99	25.62	24.99	24.12	23.07	21.85	**20.61**	20.47	18.90	17.03	19.43
Emissions e_{2A}	5.23	21.07	20.01	18.90	16.56	14.13	11.69	9.32	7.06	**5.16**	4.96	3.05	1.38	0.78
Country B														
Utility U_B	23.40	25.25	25.24	25.21	25.10	24.90	24.63	24.26	23.80	**23.31**	23.25	22.56	21.56	19.80
Production q_{1B}	30.11	26.09	26.08	26.11	26.24	26.48	26.80	27.17	27.57	**27.94**	27.98	28.36	28.56	21.41
Production q_{2B}	19.14	26.09	26.08	25.99	25.62	24.99	24.13	23.07	21.85	**20.61**	20.47	18.90	17.03	19.43
Capital K_{1B}	89.53	50.00	52.69	55.49	61.38	67.47	73.56	79.47	85.05	**89.71**	90.21	94.82	98.74	100.00
Capital K_{2B}	10.47	50.00	47.31	44.51	38.62	32.53	26.44	20.53	14.95	**10.29**	9.79	5.18	1.26	0.00
Labor L_{1B}	20.13	25.00	24.13	23.31	21.79	20.47	19.35	18.43	17.68	**17.13**	17.07	16.58	16.01	7.33
Labor L_{2A}	29.87	25.00	25.87	26.69	28.21	29.53	30.65	31.57	32.32	**32.87**	32.93	33.42	33.99	42.67
Consumption q^D_{1B}	30.11	26.09	26.08	26.11	26.24	26.48	26.80	27.17	27.57	**27.94**	27.98	28.36	28.56	21.41
Consumption q^D_{2B}	19.14	26.09	26.08	25.99	25.62	24.98	24.13	23.07	21.84	**20.61**	20.47	18.90	17.03	19.43
Emissions e_{2B}	5.23	21.07	20.01	18.90	16.56	14.13	11.69	9.32	7.06	**5.16**	4.96	3.05	1.38	0.78

a. The values of the parameters for the calibration of the BAU are in Table V.2.
b. $W = U_A + U_B - D \cdot \sum_c e_{2c}$.
c. The marginal damage of emissions is $D = 0.3$, which is the same value for both countries.
d. Policy refers to the % of emissions reductions per output with respect to the BAU scenario of both countries.
Emissions reductions per output are calculated as $IS = (1 - \%reduction) * \frac{\sum_c e_{2c}^{BAU}}{\sum_c q_{2c}^{BAU}}$.

Unilateral IS

Table V.6 presents the case of unilateral IS regulation. Only *Country A* regulates emissions by imposing a percentage reduction of emissions per output of *Good 2*. Overall welfare is maximized with a reduction of 76% in the ratio of emissions per output of *Good 2* in *Country A*, relative to the BAU case. The unilateral IS policy does not replicate the first best.

Similar to the unilateral C&T scenario, the production of *Good 1* increases in *Country A* and decreases in *Country B*. The country that does not regulate emissions increases the production of the dirty good, *Good 2*, and significantly decreases the production of the clean good, *Good 1*.

To produce more of the clean good, the country who regulates will use more capital and less labor for the production of *Good 1*. The productivity of capital will be smaller in *Country A* relative to *Country B*. In the harmonized IS case, both countries have almost identical distribution of production factors across industries, but in the unilateral IS case, capital shifts to the production of the dirty good in *Country B*.

Emissions are decreased more with harmonized policies than with unilateral policies. The harmonized IS regulation has the effect of decreasing consumption of the good that is regulated in both countries. In the unilateral IS case, the effect of the regulation is to decrease consumption of the dirty good only in *Country A*. In addition, the country that regulates will consume more of the clean good. Similar to the unilateral C&T case, consumption of *Good 1* is smaller relative to *Good 2* in *Country B*.

Table V.6. Unilateral Intensity Standard: Country A regulates emissions

	First Best	BAU[a.]	Increasingly Stringent Policies											
Welfare[b.] W	43.67	37.86	38.06	38.24	38.45	**38.47**	38.42	38.22	37.97	37.81	37.72	37.63	37.40	36.84
Total damages[c.]	3.14	12.64	12.43	12.23	11.96	**11.91**	11.89	11.99	12.15	12.22	12.17	11.99	11.32	9.44
Policy[d.]			1%	10%	20%	**24%**	30%	40%	50%	60%	70%	80%	90%	95%
Country A														
Utility U_A	23.40	25.25	25.25	25.24	25.20	**25.19**	25.16	25.11	25.06	25.01	24.95	24.81	24.36	23.14
Production q_{1A}	30.11	26.09	25.67	26.08	29.07	**30.88**	33.99	39.47	43.80	45.45	45.12	42.95	34.14	10.00
Production q_{2A}	19.14	26.09	25.90	24.88	20.86	**18.78**	15.42	9.86	5.62	3.85	3.72	4.75	9.20	19.49
Capital K_{1A}	89.53	50.00	50.09	51.70	58.78	**62.60**	68.81	78.84	85.95	88.53	88.39	85.92	73.85	26.79
Capital K_{2A}	10.47	50.00	46.98	42.48	30.98	**26.13**	19.18	9.57	3.60	1.27	0.50	0.18	0.04	0.00
Labor L_{1A}	20.13	25.00	24.30	24.43	26.92	**28.58**	31.54	37.05	41.69	43.49	43.02	40.34	30.23	7.25
Labor L_{2A}	29.87	25.00	25.70	25.57	23.08	**21.42**	18.46	12.95	8.31	6.51	6.98	9.66	19.77	42.75
Consumption q^D_{1A}	30.11	26.09	25.67	26.08	29.07	**30.88**	33.99	39.47	43.80	45.45	45.12	42.95	34.14	10.00
Consumption q^D_{2A}	19.14	26.09	26.09	26.07	25.99	**25.94**	25.87	25.73	25.60	25.51	25.44	25.35	25.00	23.93
Emissions e_{2A}	5.23	21.07	19.88	18.09	13.48	**11.53**	8.72	4.78	2.27	1.24	0.90	0.77	0.74	0.79
Country B														
Utility U_B	23.40	25.25	25.25	25.24	25.21	**25.19**	25.16	25.11	25.06	25.01	24.94	24.81	24.36	23.14
Production q_{1B}	30.11	26.09	26.50	26.09	23.12	**21.32**	18.23	12.82	8.56	6.90	7.08	8.88	16.48	37.68
Production q_{2B}	19.14	26.09	26.27	27.26	31.11	**33.11**	36.32	41.61	45.58	47.16	47.17	45.94	40.81	28.38
Capital K_{1B}	89.53	50.00	51.69	51.74	46.91	**43.47**	37.26	26.05	17.22	13.83	14.26	18.20	36.04	98.92
Capital K_{2B}	10.47	50.00	51.24	54.08	63.32	**67.80**	74.75	85.55	93.23	96.37	96.86	95.71	90.07	74.28
Labor L_{1B}	20.13	25.00	25.11	24.45	21.28	**19.53**	16.63	11.67	7.79	6.28	6.42	7.99	14.29	28.56
Labor L_{2A}	29.87	25.00	24.89	25.55	28.72	**30.47**	33.37	38.33	42.21	43.72	43.58	42.01	35.71	21.44
Consumption q^D_{1B}	30.11	26.09	26.50	26.09	23.12	**21.32**	18.23	12.82	8.56	6.90	7.08	8.88	16.48	37.68
Consumption q^D_{2B}	19.14	26.09	26.09	26.07	25.99	**25.95**	25.87	25.73	25.60	25.51	25.44	25.35	25.00	23.93
Emissions e_{2B}	5.23	21.07	21.57	22.70	26.38	**28.16**	30.92	35.20	38.24	39.48	39.67	39.22	36.97	30.68

a. The values of the parameters for the calibration of the BAU are in Table V.2.
b. $W = U_A + U_B - D \cdot \sum_c e_{2c}$.
c. The marginal damage of emissions is $D = 0.3$, which is the same value for both countries.
d. Policy refers to the % of emissions reductions per output with respect to the BAU scenario of *Country A*.
Emissions reductions per output are calculated as $IS = (1 - \%reduction) * \frac{e_{2A}^{BAU}}{q_{2A}^{BAU}}$.

V.3. Comparison across Cases

This section presents a comparison of the main variables across the cases. Alongside the tables presented in the previous sections, I use plots to explore how the main variables respond to changes in the regulation method and to changes in the percentage of emissions reductions.

Figure V.1 presents a comparison of welfare across the cases. The vertical axes show the optimized values of welfare associated with the percentage of emissions reductions shown on the horizontal axes. For the C&T cases, the horizontal axes show the percentage of reductions solely relative to emissions, and for the IS cases the percentage refers to emissions reductions relative to output. Figure V.1 shows the following ranking: the harmonized cap is superior to the harmonized intensity standard for large values of emissions reductions, and only the harmonized cap and trade case can attain the first best (represented by the green diamond).

In general, harmonized policies are superior in terms of welfare compared to unilateral policies, suggesting that lack of coordination between countries is costly in terms of welfare and that both countries would be better off if they coordinated on climate policy. In any case some regulation is preferable to no regulation, since the BAU case (represented by the red circle) reports the lowest welfare level.

In this exercise, unilateral policies closely resemble what I currently observe in several countries in the real world. The unilateral intensity standard is superior to the unilateral cap for low levels of reductions of the ratio of emissions per output imposed in *Country A*. As the cap tightens, the welfare level decreases, and the welfare level in the unilateral intensity standard scenario is lower than the rest of the cases.

Here, a second-best unilateral intensity standard policy will set the percentage of emissions per output that the dirty good can use in *Country A*. The main difference between the C&T and IS regulatory instruments is that the cap can attain the first best when it is set optimally, but only in the harmonized case and only for a single value of the cap. The IS instrument will not attain the first best, but it may be a preferred regulatory instrument under the unilateral regulation case, mainly because it does better for relatively smaller percentages of emissions reductions.

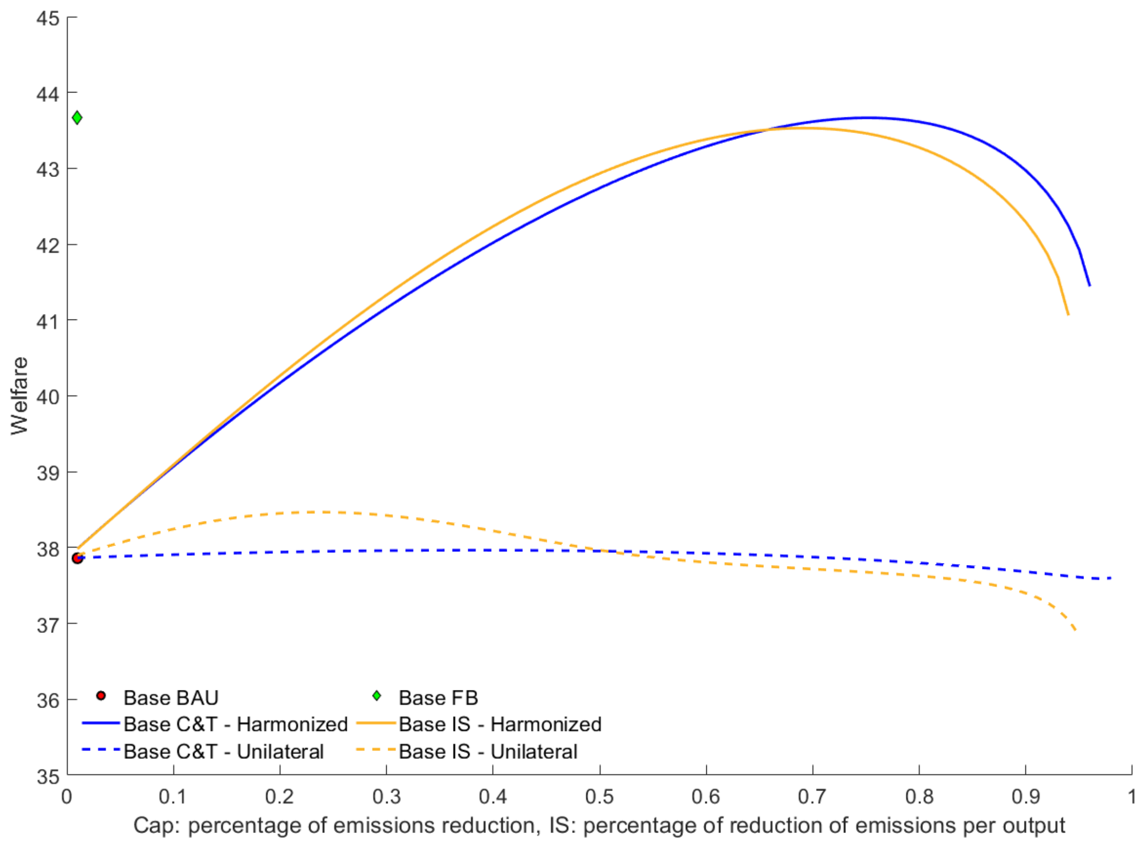


Figure V.1. Welfare

Figure V.2 compares the emissions across the cases. The vertical axes show total emissions. The horizontal axes are the same as in Figure V.1 for all remaining figures in this chapter. Emissions decrease rapidly with harmonized policies, and emissions decrease quicker in the harmonized cap case than in the harmonized intensity standard case. It is interesting to note that emissions stay almost the same for the unilateral C&T and unilateral IS cases, suggesting that unilateral emissions reductions policies might be sub-optimal for reducing emissions, although unilateral intensity standards do better than unilateral C&T, at least for small values of the policy. As can be seen in Figure V.2, unilateral policies are not good enough for reducing emissions; the contribution of unilateral policies to climate policy is marginal. An important policy recommendation would be to not expect the results of harmonized policies in terms of emissions reductions when applying unilateral policies. The graphical analysis shows that coordination pay-offs of harmonized policies are much higher.

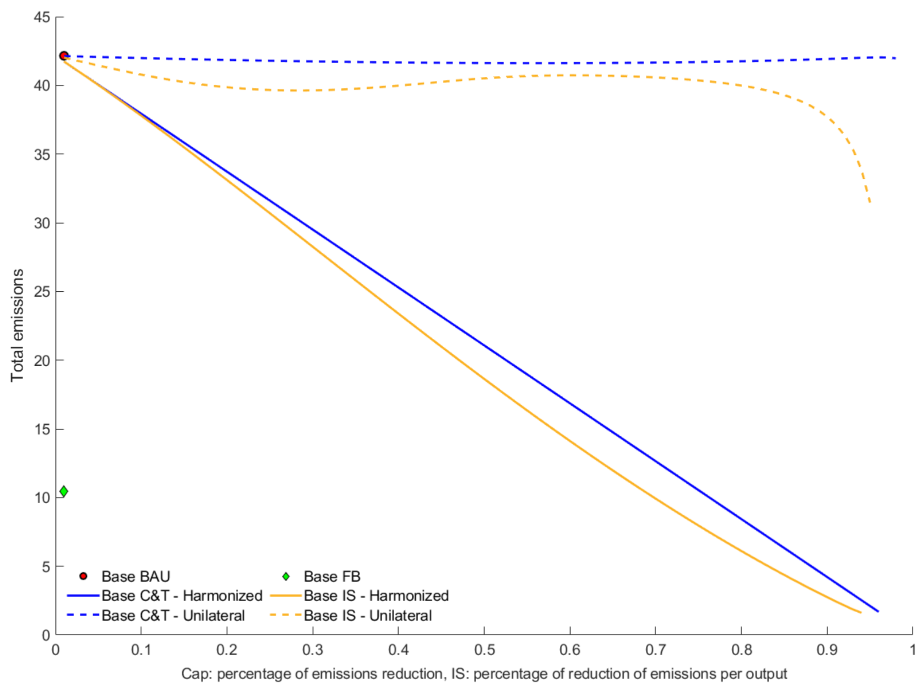


Figure V.2. Emissions

Figure V.3 shows consumption of the clean good (*Good 1*) in the left panels, and consumption of the dirty good (*Good 2*) in the right panels for both countries. Consumption of the clean good is larger than consumption of the dirty good in the harmonized cases. There are larger values of consumption of the clean good for the harmonized C&T case than for the harmonized IS case, and smaller values of consumption of the dirty good. Unilateral policies do not alter consumption much, and the unilateral cap leads to slightly less consumption of the dirty good, especially for the country that regulates. Recall that unilateral policies report lower welfare values than harmonized policies. The gap between harmonized cases and unilateral cases is presented in V.1, where unilateral policies do not report increased utility derived from consumption.

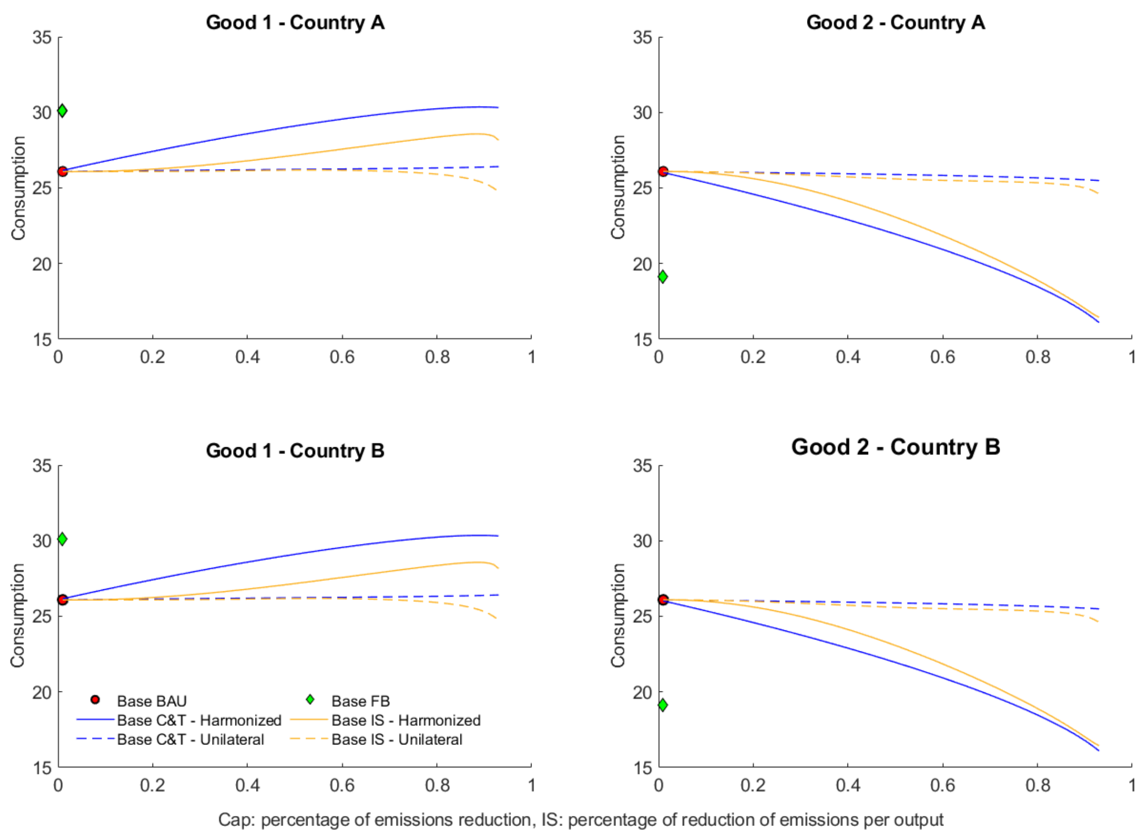


Figure V.3. Consumption

Figure V.4 shows capital usage for *Good 1* in the left panel, and capital usage for *Good 2* in the right panel. The model has interesting implications for the usage of capital. In the model, capital is mobile between countries and labor is fixed. For the case of harmonized intensity standards, the country that regulates (*Country A*) invests much more capital in the production of the clean good than in the dirty good. In the case of harmonized C&T, there are no differences in investments between the clean and dirty good. The country that regulates decreases its investments in the production of the clean and dirty good as the regulation gets tighter, and the country that does not regulate increases its investments in both goods as the regulation gets tighter. For the unilateral C&T and unilateral intensity standards cases, investment decreases in the production of the dirty good in *Country A* when the regulation tightens.

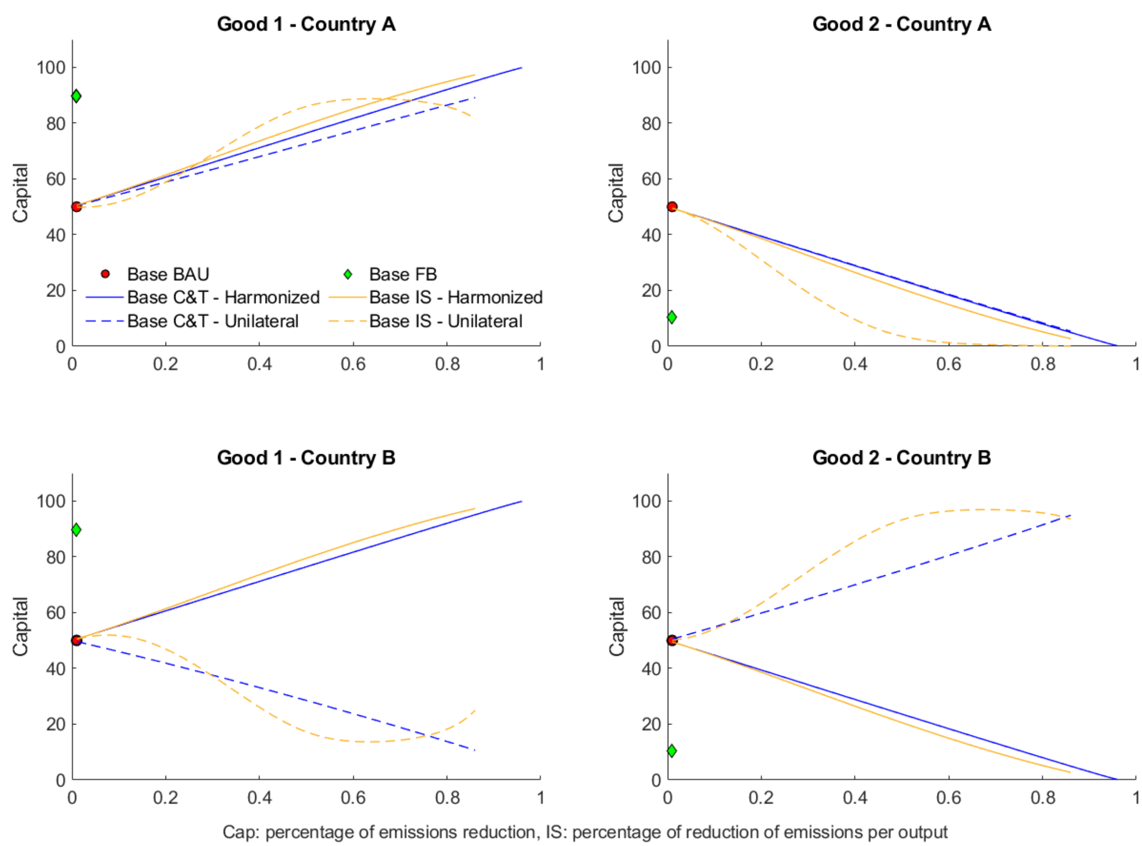


Figure V.4. Capital usage

Figure V.5 shows labor utilization in the production of *Good 1* in the left panel, and labor utilization in the production of *Good 2* in the right panel. Labor usage behaves similarly to capital, even though is not mobile across countries. For the case of harmonized intensity standards, *Country A*, the country that regulates, employs much more labor in the production of the clean good compared to the dirty good. For the harmonized cap case, there are no differences in labor across goods; the country that regulates decreases employment in the production of clean and dirty goods as the regulation tightens, and the country that does not regulate increases employment.

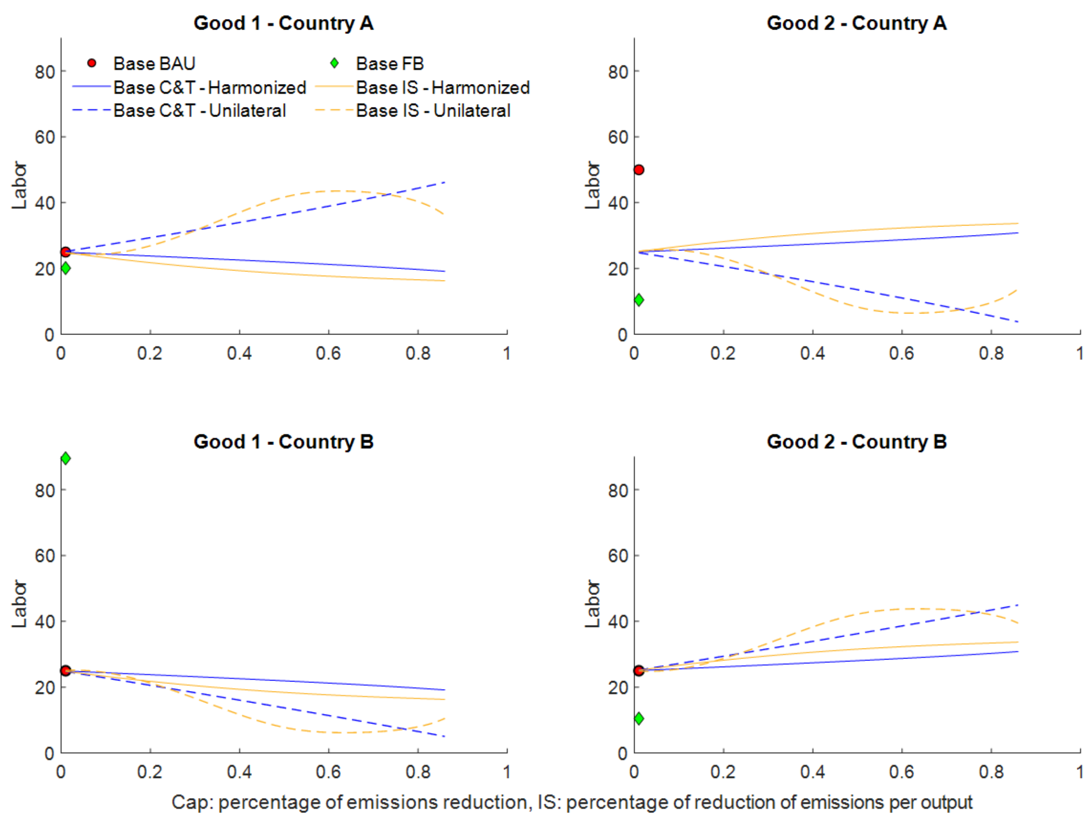


Figure V.5. Labor usage

V.4. Sensitivity Analysis

In this section, I present results of the sensitivity analysis. The purpose of this exercise is to assess the robustness of the results to the selection of the values of the parameters. I have divided the exposition into three subsections. The first presents the changes in parameters for the utility function, the second describes changes in production, and the final section presents changes in the values of the of the parameters of the production function of emissions. I rely on visual inspection of the welfare functions to draw conclusions about the effects of parameter changes in the functions of the model. In each graphic the baseline is plotted with lighter lines.

Table V.7 shows the results of different parameter changes with respect to the baseline. It is important to clarify that when changing a parameter value, the overall equilibrium is altered. To construct Table V.7, the model was solved for all possible values of the policy. Each row shows the optimized results from changing a single parameter. For simplicity's sake, the same change was applied to both countries and to both goods. For instance, a change in β in the production function was applied to the production function of *Good 1* and *Good 2* in *Country A* and in *Country B*. The corresponding value changes are from 0.3 to 0.10, and from 0.3 to 0.65 (see Table (V.1) where β affects the fourth equation). Columns two to seven in Table V.7, show the maximum welfare values for different changes in the value of the parameters for the cases described in Chapter IV.

The results show that in every case, the harmonized C&T is capable of replicating the first best, since the maximum welfare value in the first best column is equal to the maximum welfare value of the harmonized C&T scenario column. The welfare values corresponding to the Business as Usual case are also the lowest; that is, countries are better off with any regulation than with no regulation at all, and thus even incomplete regulation is better than nothing.

In addition, Table V.7 shows that the harmonized C&T scenario is superior in terms of welfare maximization to the harmonized IS scenario[2]. This corroborates the hypothesis presented in Proposition 3 in Chapter IV. The IS case (the higher welfare value for the IS) cannot attain the first best outcome.

The results of Table V.7 show that the unilateral IS scenario reports higher welfare values than the unilateral C&T scenario. This shows that under incomplete regulation and leakage, the IS regulation is capable of dominating the C&T regulation (See Proposition 5 in Chapter IV).

The results of Table V.7 show that the unilateral IS regulation can reduce as much emissions as the unilateral C&T regulation can, and can do better in terms of overall welfare. Currently in the United States, the total renewable fuel standards are not set higher than 30%[3]. This simulation exercise shows that unilateral ISs can increase to around one-fifth of the ratio of emissions reductions per output in the BAU. As most countries transition to cleaner sources of energy, it is important to note that regulations of emissions that are not higher as one-thrid will fall in this category under the current circumstances.

Table V.7 clearly shows that unilateral policies are sub-optimal in terms of welfare. Both a unilateral cap and a unilateral intensity standard will not be effective in terms of increasing welfare and reducing emissions as compared with harmonized policies. This is simply because the regulation targets only 50% of

[2]Recall that even though all solutions are optimal, there is only one value of the policy that reports the higher optimized welfare level.

[3]See epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard.

Table V.7. Comparison of Welfare across Parameter Assumptions

Parameter change	FB	BAU	C&T	IS	C&T *Country A*	IS *Country A*
Baseline[a.]	43.67	37.86	43.67	43.54	37.98	38.47
Utility						
α=0.25	45.19	39.33	45.19	45.05	39.40	39.63
α=0.65	49.38	45.60	49.38	49.25	45.68	46.14
ρ=0.05	43.47	37.86	43.47	43.36	37.95	38.46
ρ=0.75	45.06	37.86	45.06	44.81	38.11	38.54
Production						
γ=0.60	30.20	23.13	30.20	30.12	23.25	23.78
γ=0.99	51.34	46.09	51.34	51.17	46.19	46.68
β=0.10	40.47	30.70	40.47	40.46	31.13	34.75
β=0.65	53.80	51.38	53.80	52.97	51.41	51.62
ϕ=0.40	42.32	37.32	42.32	42.05	37.42	37.86
ϕ=0.80	43.67	37.86	43.67	43.53	37.97	38.47
Returns to scale						
θ=0.85	18.09	12.98	18.09	18.06	13.78	14.05
θ=0.95	33.38	27.69	33.38	33.29	28.08	28.57
Emissions						
μ=0.35	44.31	40.65	44.31	44.14	40.73	41.12
μ=0.55	43.23	35.01	43.23	43.13	35.15	35.75
δ = 0.70	42.78	38.33	42.78	42.50	38.50	38.94
δ = 0.95	43.70	37.49	43.70	43.58	37.60	38.11

a. Baseline parameter values: α=0.50, ρ=0.25, γ=0.85, β=0.30, ϕ=0.60, θ=0.99, μ=0.45, δ=0.90.
Policy: FB - First Best, BAU - Business as Usual, C&T - Cap and Trade, IS - Intensity Standard.

total emissions and not because these policies are ineffective. Extensions to heterogeneous emissions targets and relaxing the assumption of symmetry are straightforward and can be implemented easily.

The results shown in Table V.7 are extremely important for the purposes of the dissertation, since the proof of the propositions presented in the previous chapter cannot be done analytically, but with the help of a numerical exercise. Furthermore, the complexities of general equilibrium make it difficult to test the hypothesis of the superiority of the IS when there is unilateral regulation and leakage, which is why it is important to use a simple model, as is the case in this chapter.

To understand how the value of the parameters affects the results of the model, I have provided detailed descriptions of the influence of the values in Table V.7 in the figures below. I have divided the parameters according to the group descriptions in Table V.2. In each of the figures below, the vertical axes show the optimized welfare values, and the horizontal axes show the value of the policy, as in the previous figures. In general, the left panel shows a reduction in the value of the parameter and the right panel shows an increase in the value of the parameter. The baseline is graphed in its original colors (darker lines), and I used transparent colors to represent the changes in the parameters.

Parameters in the Utility Function

Figure V.6 shows the effect of changing the weight of the clean good, α. When this is increased in the production function, welfare increases proportionally in all cases, and I do not observe any changes in the curvature or shape of the lines.

Figure V.7 shows changes in the coefficient of the utility function, ρ. It is interesting to note is that, as ρ increases, there is more room for larger values of policy parameters that maximize overall welfare. Therefore, with larger values of ρ, it is possible to reduce more emissions overall. This parameter is the coefficient that determines the value of the elasticity of substitution, or how easy it is to substitute between the clean and dirty good. For values of ρ close to zero, I have the Cobb Douglas case.

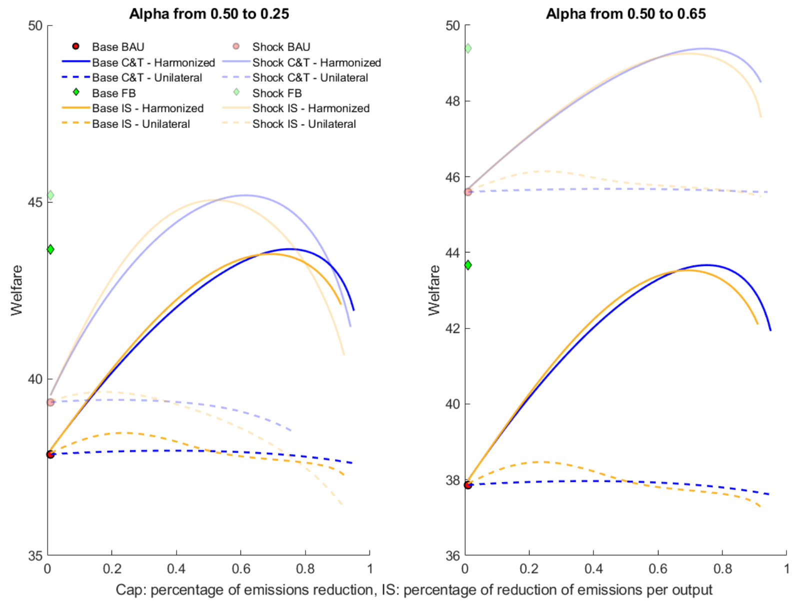


Figure V.6. Change in α - Weight of Good Q1 in the Utility Function

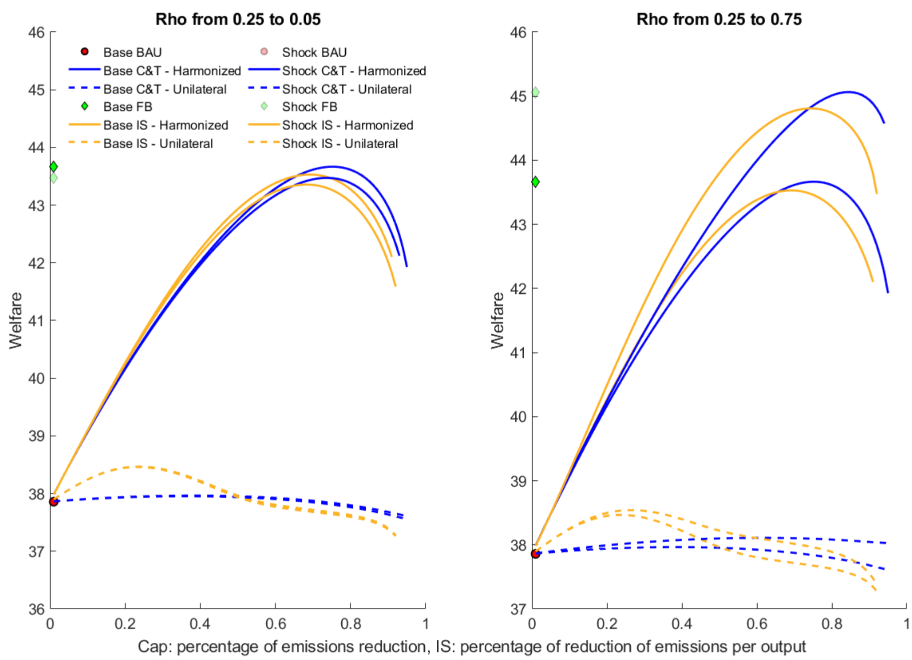


Figure V.7. Change in ρ - Coefficient in the Utility Function

Parameters in the Production Function

The effects of changing the scale parameter in the production function, γ, are presented in Figure V.8. The effects of changing γ are similar those from changing α. Changing γ shifts the problem up or down and has no effect on the ranking of the policies.

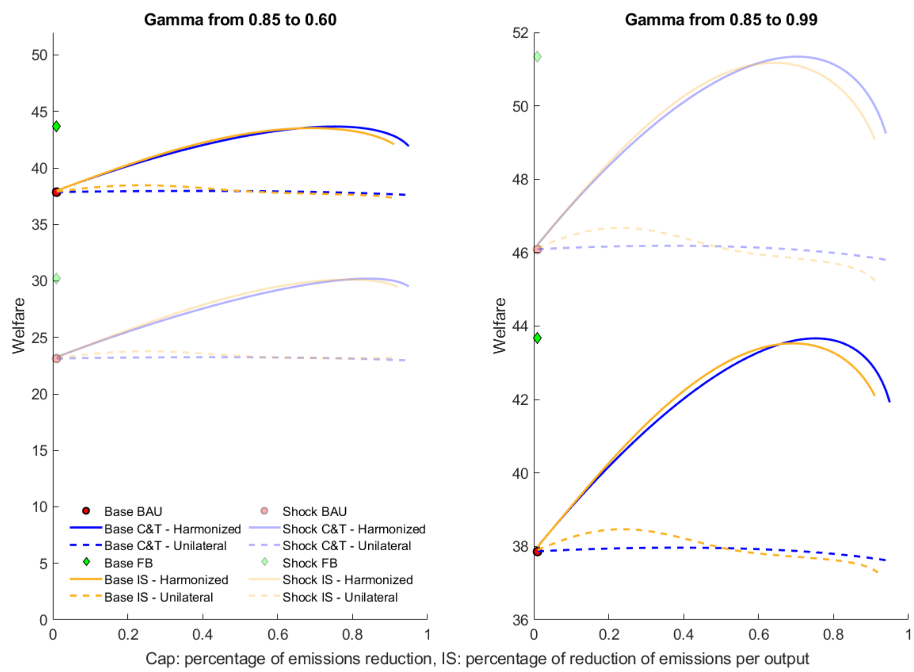


Figure V.8. Change in γ - Shift in the Production Function

The effect of changing the weight of capital in the production function is represented in Figure V.9. Changing β changes the shape of the welfare function and therefore re-scales the problem. As β gets larger, the welfare function declines quicker with tighter policy values of the regulation. The unilateral intensity standard welfare line cuts the unilateral cap at smaller values of the cap. Thus, larger values of β would widen the gap between the C&T and IS cases.

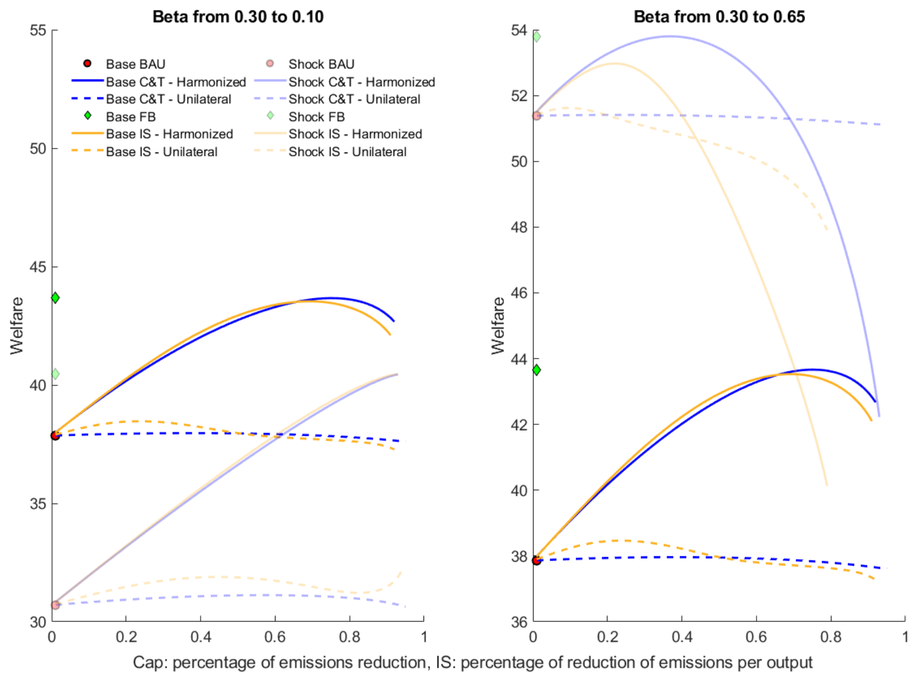


Figure V.9. Change in β - Weight of Capital in the Production Function

The effects of technological changes are presented in Figure V.10. Changes in ϕ, the technology parameter in the production function, have the same effect as changes in α and γ. The effect shifts the problem up or down the welfare lines and does not alter its shape, thus preserving the rank of the policies.

Parameters in the Emissions Production Function

Figure V.11 shows the effect of changing the weight of capital in the production function of emissions, μ. The larger μ is, the wider the gap between the unilateral and harmonized cases. Thus, the maximum welfare values correspond with a smaller reduction of emissions values in the unilateral cases. See the results of Table V.7 and Figure V.11.

Figure V.12 shows the effect of changing the technology parameter of the

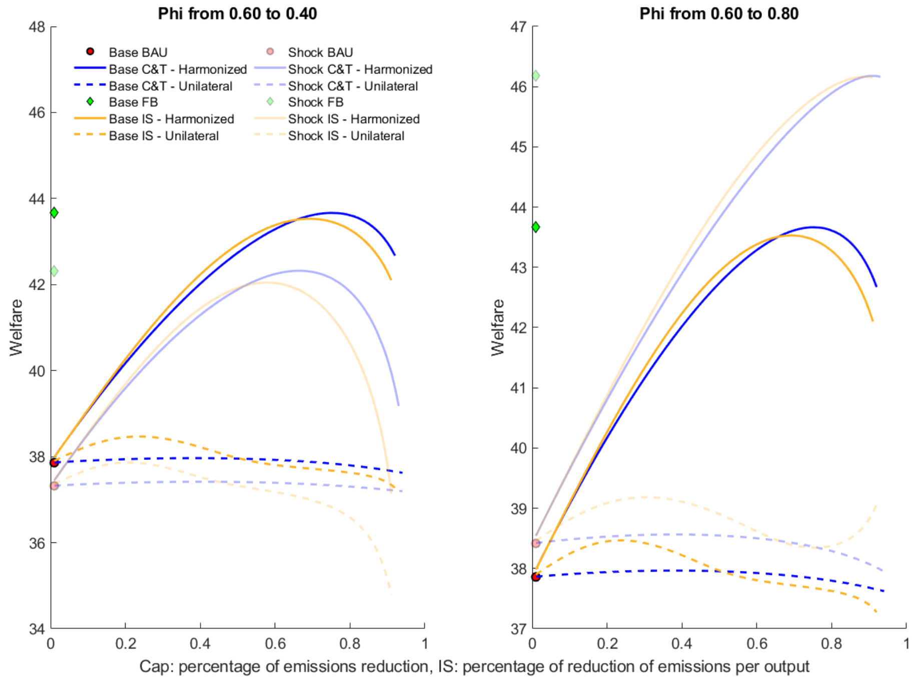


Figure V.10. Change in ϕ - Technology Parameter in the Production Function

emissions production function, δ, which plays an important role in the solution of the problem. The smaller the value of δ, the smaller the regulation policy value tolerated by the problem. Similar to the case of μ, as I increase the value of δ, the gap between harmonized and unilateral cases gets wider.

Returns to Scale Parameter

Figure V.13 shows the effect of changing the returns to scale parameter, θ, which is used in all production functions. θ plays an important role in the solution of the problem. The smaller the value of θ, the smaller the regulation policy value tolerated by the problem. Similar to the case of μ and δ, as I increase the value of δ, the gap between the harmonized and unilateral cases gets wider.

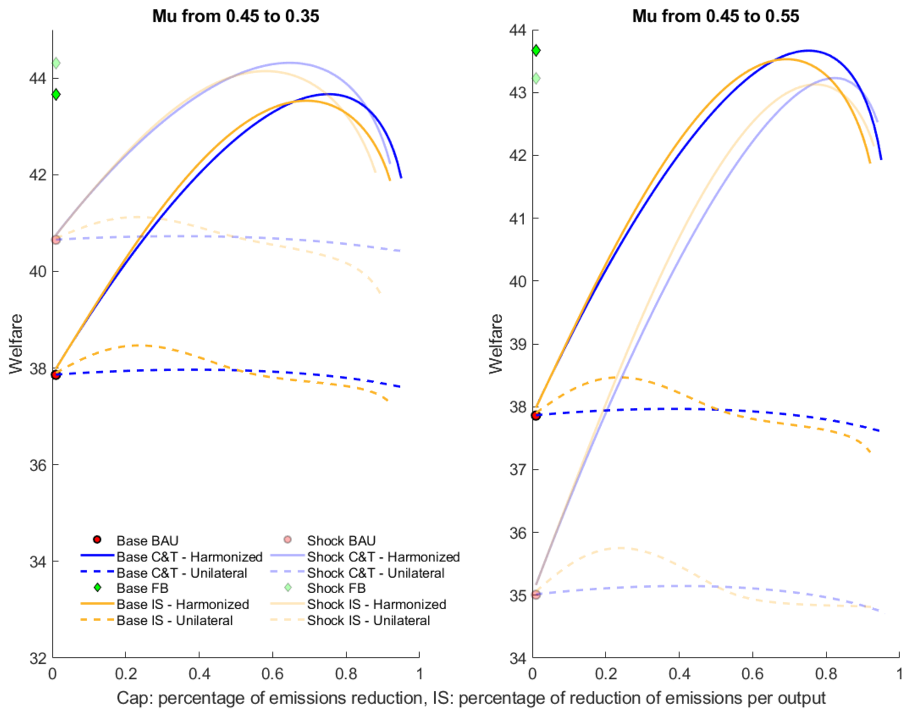


Figure V.11. Change in μ - The Weight of Capital in the Emissions Function

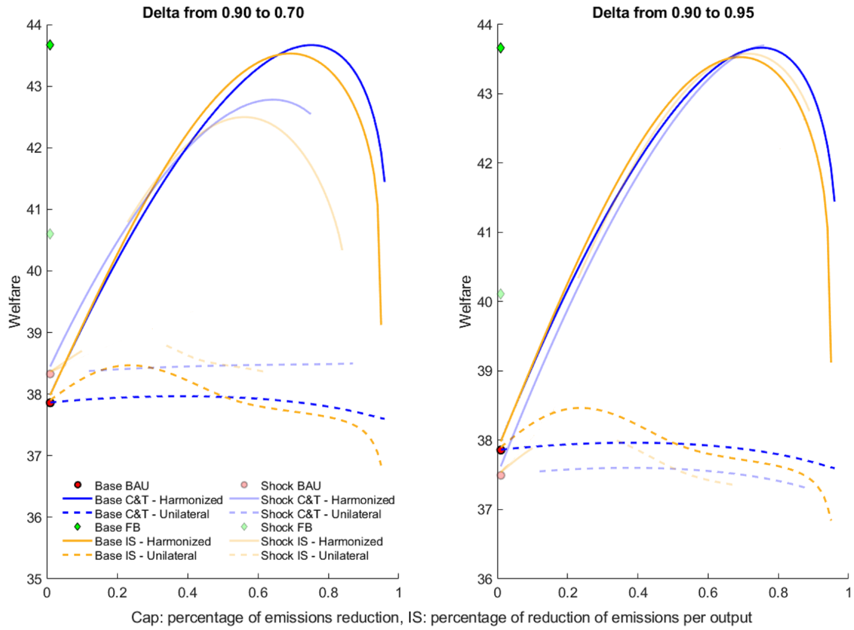


Figure V.12. Change in δ - The Technology Parameter in the Production of Emissions Function

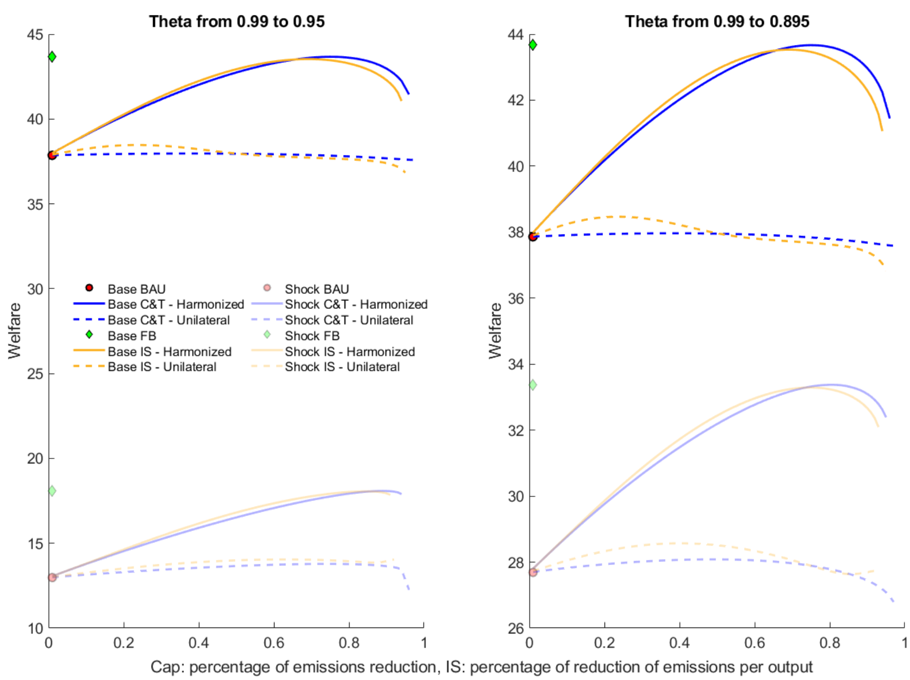


Figure V.13. Change in θ - The Coefficient of Inputs in the Production Function

V.5. Conclusion

The main conclusions of the dissertation are presented in this chapter and are summarized in Table V.7. The simple model proposed in the previous chapter is useful to implement numerical simulations and compare across cases. In addition, looking at two identical countries is useful since it allows one to isolate the effects of the regulation. In practice, there are confounding factors that make the comparison across cases a complex exercise. However, changing the parameter values or functional forms to introduce heterogeneity across countries and sectors is straightforward.

From the sensitivity analysis, I have observed that the values of the parameters and elasticities of substitution influence the results in important ways. Both consumption and production are important determinants of the shape of the problem. It is important to note that changing the parameter values does not affect the ranking of the policies; however, different parametrization for each country certainly does, especially when comparing the weight of capital in the production function, or altering the returns to scale parameters[4]. Equally important is the weight of the clean good in the utility function, as its value will determine the possibility of higher percentages of emissions regulations, and more importantly how emissions behave in relation to capital and labor.

The results also highlight the importance of synchronizing substitution possibilities with the percentage of emissions reduction targets, in both unilateral and harmonized cases. However, coordination is more important for the unilateral case because the C&T and IS lines intersect each other for certain

[4]The system will encounter infeasibilities for cases where the choice of the parameters does not make sense.

values of the policy, and there are movements of capital across countries and not only industries.

For small values of emissions reductions, the intensity standard dominates the cap and trade mechanism. When there is a unilateral regulation, it is not clear what regulatory mechanism is preferred. For large values of emissions reductions (around 50%) the cap and trade unilateral mechanism dominates the intensity standard (see Figure V.1).

Even though these results are hypothetical, their implications for policy are not minor. The results highlight the importance of taking the sensitivity of customer preferences for cleaner goods into account, and the possibility of substitution towards cleaner technologies.

CHAPTER VI

CANONICAL MODELS OF ENVIRONMENTAL REGULATIONS

With the increased presence in recent years of carbon policies at the regional or global levels (World Bank, 2019), the data and tools available for the analysis of environmental regulations have increased. Among the tools used for the analysis of such policies are computable general equilibrium (CGE) models. However, applied general equilibrium analysis is still challenging to implement because of the difficulties involved in putting together a consistent dataset of all national accounts and different economic variables for all regions and economic sectors. Despite these difficulties, CGE models have become more frequently used over the years (Babatunde et al., 2017) due to the need to measure the economic impacts in different economic sectors and production factors (Dixon et al., 2013).

This chapter describes the main elements of the GTAP model used to analyze environmental regulations. The canonical model is used to implement illustrative comparisons of cap and trade and intensity standards in the next two chapters with the aim of complementing the analysis presented in Chapter IV and Chapter V[1].

This chapter is organized as follows. The first section contains a description of the main elements and variants of the GTAP model. The second section presents the variables, sets, parameters, and main equations that I will

[1] The canonical model is based on the previous work developed at the Global Trade Analysis Project (GTAP) from the Center for Global Trade Analysis at Purdue University's Department of Agricultural Economics. The GTAP project provides a variety of data suitable for the analysis of general equilibrium policies (see notably Hertel, 1997)

utilize in the subsequent chapters. The third section presents a detailed description of the main data sources. Finally, the last section contains the conclusions.

VI.1. Variants of the Environmental Canonical CGE Model

CGE models have come to play a greater role in environmental economics because of the relationship between environmental and economic variables, which is at the core of such models (Peters, 2016b, p. 11). This section describes a canonical model called the GTAP model and its underlying databases (Aguiar et al., 2019b). A variety of CGE models are used for the analysis of energy and environmental policies, such as ADAGE, AIM, DART, EC-MSMR, ENGAGE, ENVISAGE, ENV-Linkages, EPPA, EU-EMS, EXIOMOD, FARM, GDYN, GEM-E3, GLOBIOM, GNET, ICES, IGEM, IMACLIM-R, ISSA, JRC-GEM, MAGNET, MESSAGE, MIRAGE-e, MIRAGRODEP, MONASH-Green, OECD ENV-Linkages, PACE, REMIND, TEA, USAGE, and WEG-Center (Adams and Parmenter, 2013; Chateau et al., 2014; Nong, 2020; Peters, 2016a; Roson and Britz, 2018a; van der Mensbrugghe, 2018). These models are broadly consistent in their theoretical macroeconomic structures. A recent effort led by economists has attempted to compare the macro assumptions, parameters, and trade relationships of these models (Bekkers et al., 2018, p. 11).

One thing that the models have in common is that they use the GTAP database (or at least some structure of the GTAP database) combined with alternative data sources to construct a baseline that represents the steady state in the economy. For the analysis of environmental policies, economy-wide CGE models focus on the linkages of emissions to the main economic sectors in a country and the interactions of the gains and losses of environmental policies among countries. Some of these models, however, belong to institutions or universities and are not available to the public. Therefore, the main disadvantage in the context of applied research is access to the data, models, and software that are capable of solving large systems of nonlinear equation systems [2]. Several CGE models are employed to analyze dynamic economic projections and emissions.

Recently, an open-source set of tools has become available to the public: CGEBox, one of the most advanced set of tools for the implementation of CGE models (Britz and van der Mensbrugghe, 2018a). The main advantage of CGEBox is that it makes the notation of a variety of models based on different versions of the GTAP class models and databases uniform. It is open-source and coded in GAMS, with the solvers capable of solving large systems of nonlinear equations simultaneously. In Chapter VII and Chapter VIII, I use the canonical version of GTAPINGAMS, a version formulated as MCP(Lanz and Rutherford, 2016).

VI.2. Main Elements and Structure of the Canonical CGE Model

Here, I describe the structure of the standard GTAP model that I will use in the next two chapters. The standard GTAP model is documented in several papers Aguiar et al. (2019a); Corong et al. (2017); Hertel (1997); McDougall (2005). CGE models are used for the simulation of policies and to compare the economy's status under general conditions and the current economy with what the economy will be like if certain conditions in it change. A CGE model is not a model of statistical correlations. The results of the model rely on the foundations of the

[2]The standard GTAP model is expressed in percentage changes. The model is solved using the programming language software General Equilibrium Modelling Package (GEMPACK) Dixon et al. (2013). The GAMS formulation is expressed in levels. The model is solved using the GAMS software. In GAMS, the model can be solved with constrained nonlinear optimization or with a system of nonlinear equations using a mixed complementarity problem (mcp)

underlying economics. The solution represents the relationship of real variables where only relative price matters. The model will reproduce the economy's interactions; the impact of prices is significant and the economy operates under the usual macroeconomic constraints, such as the balance of national accounts and trade balances.

The standard GTAP model assumes perfect competition, and constant returns to scale, and household preferences, which are given by a constant demand elasticity formulation (van der Mensbrugghe, 2018). GTAP is based on the Walras principle of competitive general equilibrium. In GTAP, the budget constraint is applied to all individuals, and the sum of the income is the same as the sum of the expenditures. The rationality principle applies to economic transactions; agents will have optimizing behavior, and the supply and demand will be equalized because of the role of prices. The sum of all the expenditures is the same as the sum of all the revenues; and expenditures equals income.

The basics of the model are the circular flow of the economy. A more simplified version does not include a government (as in the previous chapters) but shows the factor markets, the goods markets, and the demand and supply of all the production factors. This simple schema resembles the typical economic circular flow, where the production factors are the linkages of economic activities. The productive sectors demand factors of production such as capital and labor; the factors belong to the households that supply their work on a labor market to produce commodities. The households receive wages and rent the capital in exchange for their participation in the production process. The agents purchase local or imported services, and the demand for commodities equals the total supply. That is the basic setup of a canonical economic general equilibrium model.

A CGE model departs from a baseline that resembles the social accounting matrix (SAM). A SAM is a database that contains the economic transactions of regions or countries and economic sectors at a given point in time. The model parameters are the same as in SAM and are used to calibrate a baseline. The results look at the impact of prices, quantities, factor demands, macroeconomic balances, investments, and gross domestic product (GDP). The more equations in the CGE, the harder it gets to understand a given economic policy's transmission mechanism. The model is used to simulate exogenous shocks, structural changes (productivity or endowment), and economic policies such as trade restrictions or sectorial regulations. In the standard canonical GTAP model, income comes from production and is distributed between public and private agents and investments (the standard setup of the circular flow model).

The model assumes a constant elasticity of substitution (CES) production function with a nested structure for the intermediate goods. Production factors have a CES and include factor inputs or endowments such as capital, agricultural land, and natural resources (forest, minerals, and fossil fuels). Labor is differentiated by skill level and occupation type.

Usually, the modeler will decide how to aggregate or disaggregate regions, industries, and production factors depending on the version of the GTAP database used and the modeler definitions. The standard GTAP setup can be defined as a single country or a multi-region, as a partial or general equilibrium model, or as a comparative static or recursive dynamic model, depending on the definitions. In Chapter VII, I will use the standard general equilibrium comparative static version, and in Chapter VIII, I will use the recursive dynamic formulation. The CGEBox tool includes dynamic sets that the modeler can use to select regions, industries, activities, and dynamics (Britz and van der Mensbrugghe, 2018a). There are three main dimensions or sets: industries, i, regions, r, and factors, f as defined in the table below. Table VI.1 presents the set definitions and sector identifiers for the 76 GTAP-Power 10 sectors, including the government and investments in their most disaggregated form.

Table VI.1. Definitions of Sets

Set	Definition
r	Regions: r could represent an aggregation of the 141 regions in the GTAP-Power 10 dataset
a, i	Production sectors: origin and destination
aa	Armington aggregate: production activities, households, government, investments
f	Aggregated factors: Land, Natural resources, Capital, Skilled labor, Unskilled labor
ff	Dissagregated production factors
	Skilled labor: officials, managers, legislators, technicians and associated professionals
	Unskilled labor: clerks, service, and market sales workers
	Capital
	Land: sector-specific agricultural land
	Natural resources: forest, mineral reserves, and fossil fuels
h	Household
t	Time

Source: Own elaboration based on GTAP 10 database.

CES is a standard for all the equations. The shared parameters are multiplied by the total quantity and are distributed among sectors (Britz and van der Mensbrugghe, 2018a):

$$x_i = \alpha_i y \left(\frac{\bar{P}}{P_i} \right)^{\sigma} \lambda^{1-\sigma}, \tag{28}$$

where x_i is the aggregate demand per industry i, $\bar{P}$ is the average price, and P_i represents the industry prices, and the exponent σ is the elasticity substitution parameter [3]. α_i is the baseline shared parameter, and λ represents the total factor productivity and can be interpreted as technical progress.

The average price is calculated as follows:

$$\bar{P} = \left(\sum_i \left(\frac{P_i}{\lambda_i} \right)^{1-\sigma} \right)^{\frac{1}{1-\sigma}} \tag{29}$$

The calculation of the average price allows the model to solve. It is a nonlinear dual-price aggregator for CES equations (see Britz and van der Mensbrugghe (2018b, p. 14)). The resulting share of the total is calculated by multiplying the share by the average price exponent in the elasticity of substitution. An elasticity of substitution set to zero yields the Leontief case (commonly called a fixed factor), where the original shares remain constant. Because demands are homothetic, it is common to use a shifter variable "to update the preferences or cost structure to reflect non-Hicksian neutral technical progress" when needed (Britz and van der Mensbrugghe, 2018a).

The standard equations of the GTAP model follow the CES formulation (van der Mensbrugghe, 2018)[4]. The equations in GTAP represent a nest [5]. Associated with each CES set of n equations are the n+1 equations in the model (van der Mensbrugghe, 2018). Therefore, n equations define demand or supply quantities and one equation that clears the markets through the average price (Britz and van der Mensbrugghe, 2018a). An example is the production nest represented in Figure VI.1.

[3]As in the standard CES case, $\sigma = 1$ is the Cobb-Douglas case

[4]The homothetic case where average costs or average revenue equals marginal costs or marginal benefits.

[5]CGE models are formulated in a nested structure (a nest contains a set of equations by economic activity). For example, the production will be represented by an equation that ensures that a determined subnest is in equilibrium, such as the factor market

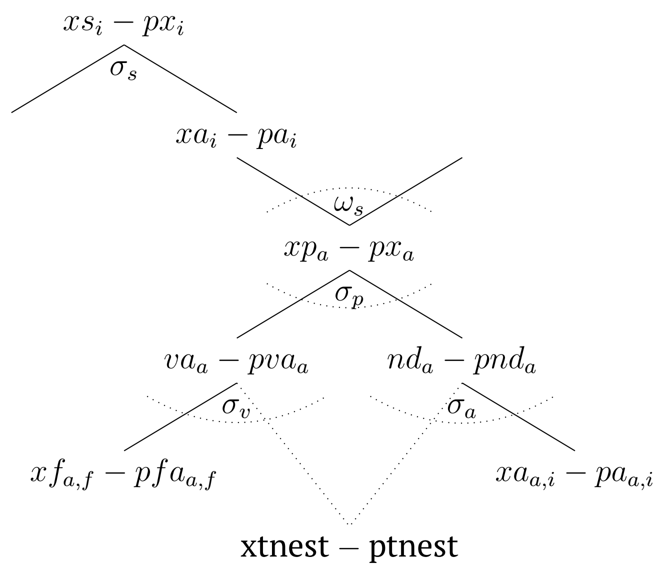


Figure VI.1. Production Nest in GTAP
Source: Extracted from Britz and van der Mensbrugghe (2018a)

The basic model equations contained in CGEBox are identical to van der Mensbrugghe (2018) for the GTAP standard formulation. Each production sector has a top-level nest and an associated expenditure share of domestic and imported goods (see Figure VI.1). The down-level nest has identical shares across all agents for import.

The standard GTAP model represents exchanges as an Armington commodity. The GTAP model uses an Armington formulation for the intermediate demand of commodities, and a value-added bundle for the factor demand. The Armington approach relies on a CES function to distribute domestic supply across industries. The production functions are CES type with substitution between the primary factors. The elasticities of substitution are defined as σ and are differentiated by nest.

In the GTAP model, there is a representative household with income to distribute between consumption of goods and savings. The demand specification has the structure of a constant difference in elasticity[6] (CDE) utility function, which resembles a CES function in the production sector (Hertel and Van der Mensbrugghe, 2016). The CDE demand specification is weighted by the ratio of vector prices relative to the minimum expenditure to attain a specific utility level (Liu et al., 2001).

The formulation of the household demand will determine the equivalent variation. Equation (30) was modified from the standard formulation to aggregate utility across regions and to subtract the damages of emissions (social cost of carbon). The objective of modifying the equivalent variation equation is to have an analogous formulation of the overall welfare function presented in Chapter IV. The standard formulation can be found in Prinn et al. (2017).

$$C\left(\frac{p}{c_o}, \sum_r (v_r - \boldsymbol{D} \cdot emis_r)\right) = \sum_i \alpha_i \sum_r (v_r - \boldsymbol{D} \cdot emis_r)^{(1-\beta_i)} \left(\frac{P_i}{c_o}\right)^{1-\beta_i} \tag{30}$$

where C is the expenditure function, P is the price vector defined in (29), and $c_o = C(P_o, u)$ is the benchmark condition for the implicit Hicksian demand. v is the indirect utility, $\boldsymbol{D}$ is the marginal damage of emissions[7], α_i is the scale parameter, β_i is the substitution parameter, and $emis$ are the emissions.

Equation (30) can be normalized setting $C(\frac{P_o}{c_o}, u) = 1$. Equation (30) becomes:

[6] https://www.gtap.agecon.purdue.edu/resources/download/4184.pdf
[7] Social cost of carbon

$$\sum_i \alpha_i \sum_r (v_r - D \cdot emis_r)^{(1-\beta_i)} \left(\frac{P_i}{c_o}\right)^{1-\beta_i} = 1 \tag{31}$$

v in this setting, is the utility that has no reduced form representation. The change in indirect utility minus the total damages of emissions, $v_r - D \cdot emis_r$, at the price P_i, will have the same effect on overall welfare as would the change in prices.

Table VI.2 defines the activity levels that characterize an equilibrium. The variables are expressed in dollar values.

The government sector is accounted for in the Armington commodity and uses taxes to provide services and for its consumption. The allocation of these two follows a CES preference function; the default elasticities are 1 for expenditures and 0 for government investments.

Trade flows in the GTAP model are based on an Armington representation of bilateral trade and on the standard assumption that production and consumption decisions have an effect on world prices depending on the value of the trade elasticities that are exogenous in the model. The regional aggregation of the model allows regions not considered in the analysis to be treated as a group with a perfectly elastic supply and without the ability to influence world prices. The model rules out the possibility of corner solutions by imposing the usual constraint that "outputs destined for the domestic and export markets are differentiated products" (see De Melo and Robinson, 1989; van der Mensbrugghe, 2018).

All GTAP datasets follow the same structure in terms of the dimensions. However, the GTAP-Power 10 version includes a disaggregation of the electricity

Table VI.2. Definitions of Main Variables in the Model

Variable	Definition
Welfare and utility	
u	Indirect utility level
EV	equivalent variation
$rgdp$	Real Gross Domestic Product
Demand and supply	
xs	Total output
xd	Total demand
xm	Total imports
xf	Factor demand
nd	Intermediate demand composite
xi	Physical investment demand
Armington demand	
xa	Armington demand
va	Value-added composite
Prices	
px	Price vector
pva	Price for the valued added
pnd	Price for the intermediate composite
pfa	Sector-specific factor price
pi	Price index of investments
Consumption	
yc	Consumption expenditures
yg	Government consumption
yi	Gross investment expenditures
Emissions	
$emis$	Emissions
$emisp$	Price of emissions

The time dimension can be included for a dynamic setting for all the variables.
Source: Own elaboration based on (Britz and van der Mensbrugghe, 2018a, p. 32).

sector. The next two sections contain a description of the database that I will use in the next two chapters, and the emissions accounting.

VI.3. GTAP-Power Database

This section describes the dataset used in the subsequent chapters. As discussed in Chapter III, one important source of emissions is electric power generation. The use of fossil fuels represents an important portion of the global emissions. Fossil fuels are associated with different sources of electricity generation, and environmental policies target different fuel types in the electricity sector. Thus, modeling the electricity sector requires data on distinct power generation technologies in a single database with a disaggregated electricity sector into power generation technologies (Peters, 2016b). Version 10 of the GTAP-Power database is the primary data source for the following chapters.

The GTAP 10 database "represents global production and trade for 141 countries or regions, 76 commodities, and eight primary factors" (Aguiar et al., 2019b). The most recent available database is for 2014 and was released in 2019. The standard GTAP database represents about 98% of the global GDP and 92% of the global population (Aguiar et al., 2019b, p. 1). The dataset also provides trade and Armington elasticities for the previous versions that were estimated for the 2004 vintage (Aguiar et al., 2016). The elasticities determine the response of the model to trade dynamics and are determinants of the final demand[8].

The standard GTAP database is combined with data from the European Commission Emission Database for Global Atmospheric Research (EDGAR) project (The European Commission Joint Research Center, 2019). The database contains the parameters needed to calibrate the equations in the GTAP model described in the previous section in a consistent database that resembles the equilibrium of national accounts (Chepeliev, 2020a). Variables such as production, intermediate demand, final demand, imports and exports, and taxes and subsidies are represented in the database. Such variables are common to almost all applied general equilibrium models (Aguiar et al., 2019b).

[8]See Aguiar et al. (2019b) for a comprehensive description of the key features of the GTAP 10 database; see Appendix B for estimates of trade elasticities that correspond to the aggregations used in this dissertation.

The GTAP-Power database represents the following technologies: coal, gas, hydro, nuclear, oil, solar, wind, and other renewable technologies (Chepeliev, 2020a,b). Peters (2016b) described the procedure for disaggregating the electricity sector in the GTAP Power database using the International Energy Agency (IEA) energy balances. This involves allocating the base and peak load power generation to each technology based on the minimized operation and maintenance and fuel costs. The data disaggregation allows for the analysis of environmental regulations that target specific electricity generation sources, such as coal, gas, and oil.

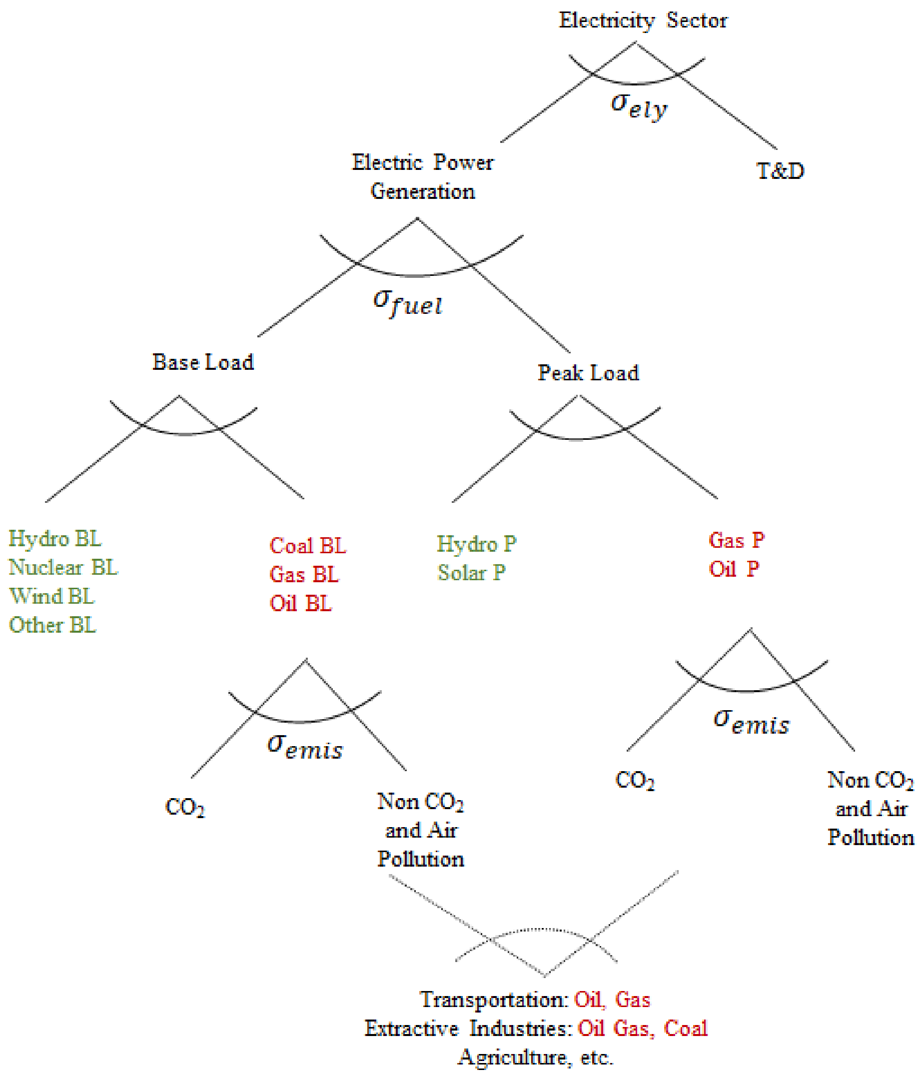
The GTAP-Power database is a good example of how emissions interact with economic variables. Using the GTAP Power database, one can analyze how clean and dirty technologies substitute for each other within an economic sector, as well as the linkages of an essential economic sector with the rest of the economy. This is possible because electric power generation in the data is represented with a nested additive constant elasticity of substitution (Chepeliev, 2020a; Chepeliev et al., 2020a) to achieve equilibrium between the demand for generation from each technology and the aggregate demand for electricity generation.

The underlying data for the disaggregation of the electricity sector are the levelized costs for each technology and region available through the energy balances published by the IEA (IEA, 2020). Two important limitations in constructing a representative dataset are the availability and quality of the data for some of the regions (Peters, 2016b). The disaggregation of the GTAP-Power database focuses mainly on supply-side disaggregation. Figure VI.2 shows the two stages of disaggregation originally performed by Peters (2016c): the disaggregation of generating technologies in the base and peak loads and the allocation of the total power generation data in the IEA energy balances to the technologies already available in the GTAP database. The original database contained an aggregated power sector representing hydro, oil, and gas generation (Peters, 2016b).

VI.4. CO_2 and non-CO_2 Emissions Accounting

The GTAP-Power data are utilized to construct the database, which includes the CO_2 emissions attached to the production sectors. The other gases are included in terms of CO_2 equivalents. To account for the emissions from power plants, the emissions from sulfur dioxide (SO_2), nitrogen oxides (NO_x), and methane (CH_4) are included as CO_2 equivalent units. The emissions data were obtained from the Joint Research Data Centre of the European Commission [9], which reports the emissions from diverse sources and sectors for most of the countries included in GTAP. A representation of the resulting electricity sector in GTAP-Power is presented in Figure VI.2. The standard GTAP models use the CES approach for nesting the demand to identify the cross-price effects (e.g., for the substitution for different electricity types)[10]. The CO_2 and non-CO_2 emissions accounting is included in the model. Recently, GTAP made data on the emissions of a variety of pollutants in the air available. In this dissertation, however, I limited the analysis to three: CH_4, NO_x, and SO_2. Such pollutants were chosen because information on them is available and because of their relative importance in the electricity sector.

[9] See edgar.jrc.ec.europa.eu. EDGAR version 5 database).
[10] See Appendix C for an estimation of the emissions' elasticities



(a)

Figure VI.2. Electricity disaggregation in GTAP
Own elaboration based on GTAP database and (Peters, 2016b)

Table VI.3. Aggregate Emissions in GTAP 10 Power Database.

Greenhouse Gas[a.]		**Electricity**[b.]	**Coal**	**Gas**	**Oil**	**Gdt**	**P_c**	**All sectors**
				ALL REGIONS				
BC	Black Carbon	116.26	455.69	7.03	68.10	22.27	1,301.20	5,172.16
CH_4	Methane	399.47	48,478.74	9,374.64	30,390.90	4,320.37	29,016.99	349,254.12
CO	Carbon monoxide	7,653.39	62,006.64	737.88	1,609.75	1,803.51	176,607.36	589,581.86
N_2O	Nitrous oxide	276.78	42.72	6.70	1.62	21.52	123.83	9,703.72
NH_3	Ammonia	119.23	1,093.50	18.36	7.20	57.74	2,271.08	48,394.66
NMVOC	Nonmethane volatile organic compounds	848.37	21,917.83	1,425.88	6,253.62	889.75	30,335.85	148,090.09
NO_x	Nitrogen oxides	31,248.35	414.85	176.03	444.67	510.42	13,418.21	124,108.36
OC	Organic carbon	114.95	360.86	3.14	15.57	9.17	3,402.44	11,730.09
PM 10	Particulate matter 10	4,735.51	6,029.13	31.95	285.34	95.22	14,299.98	61,694.69
PM 2.5	Particulate matter 2.5	2,747.57	664.14	17.56	208.67	109.02	1,905.19	38,430.99
SO_2	Sulfur dioxide	47,116.05	2,768.84	251.12	578.32	660.57	4,179.52	107,260.32
Domestic								
CO_2 (Coal)	Carbon Dioxide	7,384.52	117.40	0.00	0.07	0.24	126.95	9,922.34
CO_2 (Oil)	Carbon Dioxide	109.17	0.02	0.57	18.36	6.34	3.15	162.26
CO_2 (Gas)	Carbon Dioxide	841.67	0.17	146.88	140.28	147.73	119.68	1,920.53
CO_2 (P_c)	Carbon Dioxide	514.92	22.45	19.79	37.04	10.27	417.36	6,106.04
CO_2 (Gdt)	Carbon Dioxide	1,029.21	0.15	2.57	37.06	62.57	5.43	2,049.98
Imported								
CO_2 (Coal)	Carbon Dioxide	1,801.02	9.82	0.00	0.01	0.02	8.41	2,283.06
CO_2 (Oil)	Carbon Dioxide	25.48	0.01	0.09	8.00	1.54	1.02	39.86
CO_2 (Gas)	Carbon Dioxide	719.25	0.05	15.40	32.19	51.72	63.71	1,339.53
CO_2 (P_c)	Carbon Dioxide	199.27	4.50	2.18	4.17	2.29	119.18	2,060.77
CO_2 (Gdt)	Carbon Dioxide	16.41	0.06	0.12	1.83	0.78	1.91	81.65
				USA				
BC	Black Carbon	10.68	1.86	0.35	3.28	1.64	50.19	214.95
CH_4	Methane	62.63	2,196.14	315.78	2,294.23	926.33	5,393.56	23,878.48
CO	Carbon monoxide	853.89	287.51	10.73	230.13	464.86	24,947.11	51,287.90
N_2O	Nitrous oxide	46.04	0.06	0.09	0.15	8.36	60.54	940.35
NH_3	Ammonia	13.99	0.28	0.20	0.47	14.35	156.98	3,918.77
NMVOC	Nonmethane volatile organic compounds	82.26	749.27	51.99	373.11	275.41	2,890.09	11,202.73
NO_x	Nitrogen oxides	3,675.30	11.48	10.14	30.01	199.90	1,963.68	14,536.59
OC	Organic carbon	6.08	0.49	0.08	1.37	3.36	139.98	393.24
PM 10	Particulate matter 10	369.87	9.81	0.99	18.46	13.03	484.36	2,430.83
PM 2.5	Particulate matter 2.5	219.30	6.03	0.88	14.31	2.92	72.59	1,585.78
SO_2	Sulfur dioxide	7,232.48	16.60	22.86	95.05	240.94	117.00	9,768.14
Domestic								
CO_2 (Coal)	Carbon Dioxide	1,528.46	0.73	0.00	0.00	0.00	0.00	1,599.35
CO_2 (Oil)	Carbon Dioxide	0.08	0.00	0.06	0.12	0.51	0.00	0.98
CO_2 (Gas)	Carbon Dioxide	74.76	0.01	6.76	20.65	49.85	8.71	231.01
CO_2 (P_c)	Carbon Dioxide	24.23	6.19	3.06	7.45	6.60	66.76	1,202.05
CO_2 (Gdt)	Carbon Dioxide	437.45	0.09	0.24	0.79	22.28	0.84	853.34
Imported								
CO_2 (Coal)	Carbon Dioxide	8.44	0.00	0.00	0.00	0.00	0.00	8.68
CO_2 (Oil)	Carbon Dioxide	0.01	0.00	0.01	0.02	0.02	0.00	0.09
CO_2 (Gas)	Carbon Dioxide	12.38	0.00	1.71	5.62	3.57	15.17	69.18
CO_2 (P_c)	Carbon Dioxide	3.16	0.49	0.21	0.49	0.89	11.70	145.38
CO_2 (Gdt)	Carbon Dioxide	0.15	0.01	0.00	0.01	0.03	0.00	10.22

[a.] Greenhouse gases abbreviations: The non-CO_2 greenhouse gas (GHG) emissions are reported for three types of non-CO_2 gases; CH4 - methane, N2O - nitrous oxide, and the group of fluorinated gases (F-gases) for the year 2014.
The databases EDGAR v5.0 and EDGAR v4.2 are the source for non-agricultural emissions.
[b.] Sectors abbreviations: Coal - mining and agglomeration of hard coal, lignite and peat, Gas - extraction of natural gas, service activities incidental to oil and gas extraction excluding surveying, Oil - extraction of crude petroleum, service activities incidental to oil and gas extraction excluding surveying, Gdt - Gas manufacture, distribution, P_c - Petroleum & Coke, manufacture of coke and refined petroleum products.
Conversion factors - `https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator`
Source: GTAP 10 Database.

Table VI.3 shows the emissions of the following pollutants reported in the

GTAP database: black carbon (BC), carbon monoxide (CO), ammonia (NH_3), methane (CH_4), non-methane volatile organic compounds (NMVOCs), nitrogen oxides (NO_x), nitrous oxide (N_2O), organic carbon (OC), particulate matter 10 (PM10), particulate matter 2.5 (PM2.5), and sulfur dioxide (SO_2) (Chepeliev, 2020a; Chepeliev et al., 2020b). The emissions factors for quantifying the emissions for each pollutant and industry are from the International Institute of Applied System Analysis Greenhouse Gas and Air Pollution Interactions and Synergies (IIASA GAINS)-based model (Gidden et al., 2019) and from the Intergovernmental Panel on Climate Change (IPCC) Emissions Factors Database [11] (IPCC, 2020).

VI.5. Conclusions

This chapter describes the data and models that will be used to perform illustrative calculations in the following chapters. The GTAP standard model is a canonical model used to analyze general equilibrium policies. Because of their advantage of having a database consistent with several countries' national accounts, the GTAP data and models are a good representation of a canonical environmental model for analyzing various policies. Using the GTAP model and the database will provide a good complement for the conclusions in the previous chapters.

Both, the GTAP model, and the GTAP data are useful for analysing environmental policies. The GTAP model is publicly available and open source. The model contains variables to resemble the economic relationship, adding those extra layers will represent a good test for the conclusions of the previous

[11] https://www.ipcc-nggip.iges.or.jp/EFDB/main.php

chapters. The idea is to confirm the previous findings based on GTAP data and to provide a more nuanced picture.

CHAPTER VII

HARMONIZED AND UNILATERAL POLICIES: ILLUSTRATIVE CALCULATIONS FROM THE CANONICAL MODEL

The aim of this chapter is to use the canonical model to provide further insights into the results of the theoretical model presented in Chapter IV. The simulations presented in Chapter V are not calibrated to real-world parameters. The goal of using real-world data is to understand the general equilibrium effects of emission reductions and to learn how different environmental regulations interact with economic variables.

In this chapter, the representations of production technology, consumer preferences, and trade were adopted from the standard GTAP model. The first section describes the elements used to compare environmental regulations, such as the database, database changes, selection of commodities, and aggregations. The second section describes the implementation of the policy and the alternative scenarios of comparison. The third section presents the results and discussion. The last section provides the conclusion. The comparison performed is about the efficacy of policies in terms of maximizing the aggregated equivalent variation (EV) minus the damages caused by the emissions across regions. The real gross domestic product (RGDP) is also presented as a comparison variable. Both variables lead to equivalent results. The simulation exercise focuses on two hypothetical cases: the first case involving regulating all economic sectors and the second case involving regulating the electricity production sector and targeting fossil fuel power generation.

The comparison is made using two regions, the United States (USA) and the rest of the world (ROW), and six aggregated commodities (food, manufacturing, services, electricity generation based on fossil fuels, electricity generation based on renewable sources, and electricity transmission and distribution). The scenario comparison is similar to the cases presented in Chapter IV. There are two harmonized cases and two unilateral cases for each regulatory instrument: cap and trade (C&T) and intensity standards (IS).

VII.1. Country and Commodity Aggregation

The sectors in the GTAP power database are presented in Table VII.1. To aggregate the data, I used the 76 commodity classifications and their descriptors given in Table B.1. I aggregated the database into six commodities to make it easier to analyze the effects of environmental regulations. Region aggregation was straightforward; I isolated the USA as one region and grouped the other regions together as the ROW. The aggregation of the countries is considered less harmful than the aggregation of the commodities. The most common concern is the aggregation bias, which refers to the possibility of bias in the simulation results due to aggregation (Britz and van der Mensbrugghe, 2016; Cleveland et al., 2000; Miller and Shao, 1990).

Britz and van der Mensbrugghe (2016)'s contribution is important because their research highlights the relevance of using disaggregated pre-model estimation to construct the baseline so that the aggregation bias can be reduced. Other studies have discussed the aggregation of elasticities for CGE models and its consequences, highlighting the importance of preserving sectorial detail (Horridge, 2018). The aggregation bias becomes more relevant when implementing sector-specific policies. However, the aggregation in this chapter facilitates the analysis of the conclusions in Chapter V when looking at the effects of a “clean” sector versus a “dirty” one. Another advantage of an aggregated model is that it is easy to calibrate and converge.

For the case of regulating the fossil fuel electricity power generation, it is important to note that there will be strong linkages across industries because the fossil fuel sector is also categorized as part of the manufacturing sector. Fossil fuels are also present in the accounts of GTAP as extractive industries, such as the coal, oil, and gas production industries (see Table B.1; the GTAP database contains accounts for extractive industries such as *oil*, *coal*, *gas*, *petroleum products*, and *gas manufacture and distribution*).

I expect that when a regulatory policy is imposed on fossil fuel power generation, the general equilibrium effects will manifest in the manufacturing industry. The regulation of the fossil fuel industry will affect the manufacturing industry even when the manufacturing industry remains unregulated, and will have implications on the international trade of commodities, especially in unilateral cases. In Chapter VIII, I will present a disaggregated manufacturing sector to provide more insight into the general equilibrium effects. I also expect strong linkages across power generation technologies. The fossil fuel generation category includes the coal, gas, and oil generation technologies while the renewable category includes the hydro, solar, and wind generation technologies. Other relevant accounts are nuclear power generation and transmission and electricity distribution.

Table VII.1 summarizes the information on the aggregation used for the illustrative calculations in this chapter. The 76 sectors and 141 regions in the

GTAP database were reduced to six sectors and two regions.

Table VII.1. Sector and Regions in the Aggregation Of Chapter VII

Economic Sectors	
Food	Agriculture and food processing
Mnfc	Manufacturing (includes coal, oil and gas manufacturing)
Serv	Services
Power Generation	
Fos	Coal, gas, oil
Ren	Nuclear, wind, hydro, solar,other
TnD	Transmission and Distribution of Electricity
Regions	
USA	United States
ROW	Rest of the World

VII.2. Constraints on Emissions

Table VII.2 shows the illustrative notation for implementing the constraints of emissions in the canonical model. The top panel shows Scenario 1, in which the regulation is applied to all economic sectors. The cases of Scenario 1 correspond to the cases presented in Chapter IV: the harmonized[1] and unilateral policy cases. Each policy has two cases: the C&T case and the IS case. Similarly, the bottom panel presents the constraints of emissions of Scenario 2. The only difference between Scenario 1 and 2 is that Scenario 2 regulates emissions from fossil fuel power generation. For each scenario, there are four simulations, as in Chapter V: the harmonized C&T case, the unilateral C&T case, the harmonized IS case, and the unilateral IS case.

[1] Somebody can think about regulating global emissions in the harmonized case of Scenario 1.

Table VII.2. Implementation of Environmental Regulations in the CGE Model

Scenario 1: Regulating emissions from all economic sectors

Harmonized policies

$C\&T$	$\sum\limits_{r,a} emis(r,a) = \sum\limits_{r,a} emis_{BAU}(r,a) * (1 - pol)$
IS	$\frac{\sum\limits_{r,a} emis(r,a)}{\sum\limits_{r,a} xs(r,a)} = \frac{\sum\limits_{r,a} emis_{BAU}(r,a)}{\sum\limits_{r,a} xs_{BAU}(r,a)} * (1 - pol)$

Unilateral policies

$C\&T_U$	$\sum\limits_{a} emis(USA,a) = \sum\limits_{a} emis_{BAU}(USA,a) * (1 - pol)$
IS_U	$\frac{\sum\limits_{a} emis(USA,a)}{\sum\limits_{a} xs(USA,a)} = \frac{\sum\limits_{a} emis_{BAU}(USA,a)}{\sum\limits_{a} xs_{BAU}(USA,a)} * (1 - pol)$

Scenario 2: Regulating emissions from power generation

Harmonized policies

$C\&TFOS$	$\sum\limits_{r} emis(r,fos) = \sum\limits_{r} emis_{BAU}(r,fos) * (1 - pol)$
$ISFOS$	$\frac{\sum\limits_{r} emis(r,fos)}{\sum\limits_{r} xs(r,fos)} = \frac{\sum\limits_{r} emis_{BAU}(r,fos)}{\sum\limits_{r} xs_{BAU}(r,fos)} * (1 - pol)$

Unilateral policies

$C\&TFOS_U$	$emis(USA,fos) = emis_{BAU}(USA,fos) * (1 - pol)$
$ISFOS_U$	$\frac{emis(USA,fos)}{xs(USA,fos)} = \frac{emis_{BAU}(USA,fos)}{xs_{BAU}(USA,fos)} * (1 - pol)$

As presented in Chapter V, the harmonized C&T case will regulate the emissions for all regions and economic sectors, and the harmonized IS case will regulate the emissions for all regions and economic sectors divided by the total output (xs). In GTAP, xs is the total supply of a product in the economy that includes imported and domestic goods. In the unilateral case, the regulation applies only to the USA. In Table VII.2, $emis_{BAU}$ represents the baseline value of emissions. The percentage of emission reduction is represented as pol. For the unilateral regulation case, the set r is replaced with USA because the regulation is applied only in the USA. For the regulation of fossil fuel power generation, the set a is replaced with fos to indicate that only the fossil fuel electricity generation is regulated.

VII.3. Illustrative Calculations

In this section, I will discuss several simulations to illustrate the application of environmental regulations in the canonical model. I will report simulations that illustrate the importance of targeting regulations to set carbon prices globally, and the importance of complete regulation. The Scenario 1 and 2 results are suitable for aiding in the understanding of the environmental policies' role. In these simulations, I consider the economic impact of the unilateral regional carbon price and compare C&T systems with IS systems. For illustrative purposes, I will focus only on the results for the USA and ROW. The top panel of Table VII.3 contains the change (as a simple difference) in emissions with respect to the baseline. The lower panel contains the change in output with respect to the baseline.

The regulatory policy separates the results in each panel of Table VII.3: BAU, C&T, and IS. To construct Table VII.3, for each case, I solved the model to find the policy value that reports the higher value of the aggregated equivalent variation minus the emissions priced by the social cost of carbon reported by the

Table VII.3. Welfare and Emissions Scenario Comparison based on GTAP 10 -Power Database (Social Cost of Carbon $36 per metric ton of CO2)

Scenario[a.]	Region	Emissions Reductions[b.]	Real GDP ($ billion)	Welfare[c.]	Price CO2eq ($/Mt.Ton)[d.]	Emissions (Billion tons CO2eq)[e.] Food & Agric.	Manuf. & Transp.	Serv.	Elec. Fos.	Elec. Ren.	Elec. TnD.	Total[f.]
BAU	ROW	0.00	60.14	33.54	0.00	0.506	5.472	4.852	9.730	0.015	0.035	20.612
BAU	USA	0.00	17.20	11.98	0.00	0.106	0.464	1.405	2.067	0.001	0.001	4.044
BAU	World[2]	0.00	77.34	45.53	0.00	0.612	5.937	6.257	11.798	0.016	0.036	24.656
Scenario: Regulating emissions from all economic sectors						**Change with respect the BAU**						
Harmonized Policies												
$C\&T$	ROW	2.20	1.26%	2.01%	32.06	0.000	0.118	-0.053	-0.518	0.000	0.000	-0.453
$C\&T$	USA	2.20	0.98%	1.00%	32.06	0.000	0.012	-0.015	-0.086	0.000	0.000	-0.089
$C\&T$	World	2.20	1.20%	1.74%	32.06	0.000	0.130	-0.068	-0.604	0.000	0.000	-0.542
IS	ROW	2.10	1.26%	2.00%	31.81	0.000	-0.089	0.002	-0.345	0.000	0.000	-0.433
IS	USA	2.10	0.97%	1.00%	31.81	0.000	0.062	-0.001	-0.146	0.000	0.000	-0.085
IS	World	2.10	1.19%	1.74%	31.81	0.000	-0.028	0.001	-0.491	0.000	0.000	-0.518
Unilateral Policies												
$C\&T_U$	ROW	NA	1.18%	1.63%	NA	-0.001	-0.257	-0.032	-0.030	0.006	0.025	-0.291
$C\&T_U$	USA	8.30	0.78%	1.75%	58.86	0.001	-0.048	-0.002	-0.287	0.000	0.001	-0.336
$C\&T_U$	World	2.54	1.09%	1.66%	NA	-0.001	-0.305	-0.034	-0.318	0.006	0.025	-0.626
IS_U	ROW	NA	1.19%	1.65%	NA	-0.001	-0.024	-0.108	-0.001	0.006	0.025	-0.070
IS_U	USA	8.20	0.83%	1.73%	58.26	0.001	0.067	-0.005	-0.395	0.000	0.001	-0.732
IS_U	World	1.77	1.11%	1.67%	NA	-0.001	0.043	-0.113	-0.397	0.006	0.025	-0.802
Scenario: Regulating emissions from power generation						**Change with respect the BAU**						
Harmonized Policies												
$C\&TFOS$	ROW	4.40	1.18%	1.78%	31.50	0.000	-0.011	0.002	-0.898	0.000	0.000	-0.907
$C\&TFOS$	USA	4.40	0.72%	1.23%	31.50	0.000	-0.067	-0.100	-0.011	0.000	0.000	-0.178
$C\&TFOS$	World	4.40	1.08%	1.63%	31.50	0.000	-0.078	-0.098	-0.908	0.000	0.000	-1.085
$ISFOS$	ROW	3.80	1.18%	1.81%	33.79	0.000	-0.014	0.002	-0.772	0.000	0.000	-0.783
$ISFOS$	USA	3.80	0.71%	1.11%	33.79	0.000	0.000	-0.001	-0.153	0.000	0.000	-0.154
$ISFOS$	World	3.80	1.07%	1.63%	33.79	0.000	-0.013	0.002	-0.925	0.000	0.000	-0.937
Unilateral Policies												
$C\&TFOS_U$	ROW	NA	1.18%	1.63%	NA	-0.001	-0.023	-0.008	-0.002	0.006	0.025	-0.003
$C\&TFOS_U$	USA	18.20	0.79%	1.77%	56.75	0.001	0.001	-0.002	-0.737	0.000	0.001	-0.736
$C\&TFOS_U$	World	3.00	1.09%	1.67%	NA	-0.001	-0.022	-0.010	-0.739	0.006	0.025	-0.739
$ISFOS_U$	ROW	NA	1.19%	1.63%	NA	-0.001	-0.033	-0.064	-0.002	0.006	0.025	-0.104
$ISFOS_U$	USA	18.10	0.84%	1.77%	57.45	0.001	-0.222	-0.002	-0.510	0.000	0.001	-0.332
$ISFOS_U$	World	3.25	1.11%	1.67%	NA	-0.001	-0.255	-0.066	-0.511	0.006	0.025	-0.435

a. Policy Abbreviations: BAU - Business as Usual, C&T - Cap and Trade, IS - Intensity Standard. Subscript U denotes unilateral regulations, in those cases only USA regulates emissions. Cases labeled with 'FOS' denote that the regulation was applied only to the fossil fuel electricity generation.
b. For the C&T scenarios, emissions reductions is the % of emissions reductions with respect to the BAU. For the IS scenarios, the emissions is the % of emissions reductions per output with respect to the BAU scenario. World emissions reductions is the total % of emissions reductions with respect to the BAU.
c. Welfare is equivalent variation minus the social cost of carbon at reported by EPA for 2015 $36 per metric ton CO_{2eq}. See `https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html`
d. CO2eq: carbon dioxide equivalent units. Mt. Ton: metric tons.
e. Sectors and regions abbreviations: ROW - Rest of the World, USA - United States, Food & Agric. - Food and Agriculture, Manuf. & Transp. - Manufacturing and Transportation, Serv. - Services, Elec. Fos. - Fossil power generation, Elec. Ren.- Renewable power generation, Elec. TnD. - Electricity Transmission and Distribution, NA - not available, World represents the geographic coverage in the GTAP 10 database and not necessarily means a complete representation of the globe. Total emissions might not correspond to the overall global emissions registered in 2014 but to the sectors and regions registered in the GTAP database.
Source: Own elaboration based on GTAP 10 database.

Environmental Protection Agency (EPA) for 2015 $36 per metric ton of CO_2[3]. This type of analysis is often implemented to find the policy value that maximizes

[3]Please see `https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html`

Table VII.4. Welfare and Emissions Scenario Comparison based on GTAP 10 -Power Database (Social Cost of Carbon USD \$100 per metric ton of CO2)

Scenario[a.]	Region	Emissions Reductions[b.]	Real GDP ($ billion)	Welfare[c.]	Price CO2eq ($/Mt.Ton)[d.]	Emissions (Billion tons CO2eq)[e.] Food & Agric.	Manuf. & Transp.	Serv.	Elec. Fos.	Elec. Ren.	Elec. TnD.	Total[f.]
BAU	ROW	0.00	58,819.32	31,483.38	0.00	0.506	5.472	4.852	9.730	0.015	0.035	20.612
BAU	USA	0.00	16,943.71	11,580.19	0.00	0.106	0.464	1.405	2.067	0.001	0.001	4.044
BAU	World	0.00	75,763.03	43,063.57	0.00	0.612	5.937	6.257	11.798	0.016	0.036	24.656
Scenario: Regulating emissions from all economic sectors						**Change with respect the BAU**						
Harmonized Policies												
$C\&T$	ROW	4.20	3.71	13.58	100.97	0.000	-0.295	-0.053	-0.518	0.000	0.000	-0.866
$C\&T$	USA	4.20	3.22	9.34	100.97	-0.001	-0.068	-0.015	-0.086	0.000	0.000	-0.170
$C\&T$	World	4.20	3.60	12.44	100.97	-0.001	-0.362	-0.068	-0.604	0.000	0.000	-1.036
IS	ROW	5.10	3.60	13.44	95.84	0.000	-0.708	0.002	-0.345	0.000	0.000	-1.051
IS	USA	5.10	2.90	9.27	95.84	0.000	-0.060	-0.001	-0.146	0.000	0.000	-0.206
IS	World	5.10	3.45	12.32	95.84	0.000	-0.767	0.001	-0.491	0.000	0.000	-1.257
Unilateral Policies												
$C\&T_U$	ROW	NA	3.71	13.58	NA	-0.001	-0.257	-0.032	-0.030	0.006	0.025	-0.291
$C\&T_U$	USA	10.70	3.22	9.34	131.49	0.001	-0.145	-0.002	-0.287	0.000	0.001	-0.433
$C\&T_U$	World	2.93	3.60	12.44	NA	-0.001	-0.402	-0.034	-0.318	0.006	0.025	-0.723
IS_U	ROW	NA	3.60	13.44	NA	-0.001	-0.024	-0.108	-0.001	0.006	0.025	-0.104
IS_U	USA	7.40	2.90	9.27	135.84	0.001	0.100	-0.005	-0.395	0.000	0.001	-0.299
IS_U	World	1.64	3.45	12.32	NA	-0.001	0.076	-0.113	-0.397	0.006	0.025	-0.403
Scenario: Regulating emissions from power generation						**Change with respect the BAU**						
Harmonized Policies												
$C\&TFOS$	ROW	6.30	3.71	13.58	106.01	0.000	-0.011	0.002	-1.289	0.000	0.000	-1.299
$C\&TFOS$	USA	6.30	3.22	9.34	106.01	0.000	-0.067	-0.100	-0.087	0.000	0.000	-0.255
$C\&TFOS$	World	6.30	3.60	12.44	106.01	0.000	-0.078	-0.098	-1.377	0.000	0.000	-1.553
$ISFOS$	ROW	12.50	3.60	13.44	116.52	0.000	-0.014	0.002	-2.565	0.000	0.000	-2.576
$ISFOS$	USA	12.50	2.90	9.27	116.52	0.000	0.000	-0.001	-0.505	0.000	0.000	-0.506
$ISFOS$	World	12.50	3.45	12.32	116.52	0.000	-0.013	0.002	-3.070	0.000	0.000	-3.082
Unilateral Policies												
$C\&TFOS_U$	ROW	NA	3.71	13.58	NA	-0.001	-0.023	-0.008	-0.002	0.006	0.025	-0.003
$C\&TFOS_U$	USA	16.90	3.22	9.34	145.32	0.001	0.001	-0.002	-0.684	0.000	0.001	-0.683
$C\&TFOS_U$	World	2.79	3.60	12.44	NA	-0.001	-0.022	-0.010	-0.686	0.006	0.025	-0.687
$ISFOS_U$	ROW	NA	3.60	13.44	NA	-0.001	-0.033	-0.064	-0.002	0.006	0.025	-0.070
$ISFOS_U$	USA	14.80	2.90	9.27	146.47	0.001	-0.222	-0.002	-0.376	0.000	0.001	-0.599
$ISFOS_U$	World	2.71	3.45	12.32	NA	-0.001	-0.255	-0.066	-0.378	0.006	0.025	-0.668

a. Policy Abbreviations: BAU - Business as Usual, C&T - Cap and Trade, IS - Intensity Standard. Subscript U denotes unilateral regulations, in those cases only USA regulates emissions. Cases labeled with 'FOS' denote that the regulation was applied only to the fossil fuel electricity generation.
b. For the C&T scenarios, emissions reductions is the % of emissions reductions with respect to the BAU. For the IS scenarios, the emissions is the % of emissions reductions per output with respect to the BAU scenario. World emissions reductions is the total % of emissions reductions with respect to the BAU.
c. Welfare is equivalent variation minus the social cost of carbon assumed at \$100 per metric ton CO_{2eq}.
d. CO2eq: carbon dioxide equivalent units. Mt. Ton: metric tons.
e. Sectors and regions abbreviations: ROW - Rest of the World, USA - United States, Food & Agric. - Food and Agriculture, Manuf. & Transp. - Manufacturing and Transportation, Serv. - Services, Elec. Fos. - Fossil power generation, Elec. Ren.- Renewable power generation, Elec. TnD. - Electricity Transmission and Distribution, NA - not available, World represents the geographic coverage in the GTAP 10 database and not necessarily means a complete representation of the globe. Total emissions might not correspond to the overall global emissions registered in 2014 but to the sectors and regions registered in the GTAP database.
Source: Own elaboration based on GTAP 10 database.

welfare. Policymakers generally assume an exogenous carbon price and describe a given policy's effects on the overall economy. However, a given carbon price will result in an equilibrium that is probably not the optimum. In this chapter, a welfare maximizer equilibrium is reported with its associated endogenous carbon price. The amount of emission reduction is given by the policy that maximizes the overall welfare.

As I did in Chapter V, I solved the model for every possible value of the policy to identify the equilibrium that would report the higher welfare. Table VII.3 I reports the maximum RGDP and maximum EV value minus the damages caused by the emissions. The subscript “U” denotes unilateral cases. The sectorial regulation is indicated by “FOS”; for example, $C\&TFOS_U$ refers to the unilateral C&T regulation applied to fossil fuel for electricity generation.

Here, “harmonized” refers to all regions implementing coordinated regulatory policies. It does not necessarily mean complete regulations; some of the sectors in Scenario 2 remain unregulated in both regions. The relative prices play an essential role in the solution of the model. The carbon price and emissions are endogenous for all cases. It is important to note that unilateral cases correspond to a setup where the carbon price is determined locally whereas harmonized cases determine the global carbon price.

In Table VII.3, the EV values are larger for the C&T harmonized cases than for the IS harmonized cases. This is true for both the regulation of all economic sectors and the regulation of fossil fuel for power generation. The welfare values for the harmonized cases are larger than those for the unilateral cases. The RGDP values are also larger for the C&T harmonized cases than for the unilateral cases. The resulting carbon price is lower for the harmonized cases.

The largest change in emissions is achieved with IS cases. The result is consistent with those of Chapter V: the IS cases report the largest welfare values for unilateral regulation. In the GTAP-Power 10 database, the average emission reduction amounts compared to the baseline range from 2 to 4% in the harmonized cases and from 8 to 18% in the unilateral cases. The results of the GTAP staandard model suggest that the optimal policy depends on whether or not countries coordinate environmental regulations in both cases (i.e., regulating all economic sectors and regulating only the fossil fuel power generation sector), the same conclusions as in Chapter V. In the end, electricity power generation can be seen as a global technology because most countries tend to use the same technologies to produce electricity. Furthermore, global companies incur similar costs when producing electricity.

The bottom panel of Table VII.3 presents the results of production. The results change dramatically for the unilateral cases. The production in manufacturing and services is reduced more significantly in the unilateral cases than in the harmonized cases in the ROW. Gains in the ROW manifest in the electricity sector, producing more of the “dirty” and “clean” goods in the electricity sector when the USA regulates the power industry.

Table VII.4 serves as a sensitivity analysis presenting the case of $100 as a social cost of carbon. A different baseline is obtained, when a larger social cost of carbon is used to discount emissions from the aggregated equivalent variation, therefore the equilibrium results are different as the ones presented in Table VII.3. The results show larger endogenous carbon prices, and depending on the economic sector and policy, larger emissions reductions. Table VII.4 has the purpose to illustrate the role of the social cost of carbon, the results of the rest of the chapter rely on the case of $36 as a social cost of carbon.

Table VII.6 shows that the distribution of the production factors is altered equally for the C&T and IS cases. However, the C&T case has less effects on the capital reductions in the manufacturing sector and fossil fuel industry than the IS case.

Table VII.7 shows the reductions of the capital and labor production factors in the renewable energy and fossil fuel industries. The ROW reduces the capital investments in the renewable energy sector when the USA implements unilateral regulations in the fossil fuel industry. The increments of capital and skilled labor in the fossil fuel industry are smaller in relation to the reductions of capital investments in the renewable energy sector.

The IS unilateral regulation has effects on the production factors in the country or region that regulates them. Table VII.7 shows that the labor reductions in the fossil fuel sector will go to the manufacturing sector and that there will be a reduction in capital in the countries that do not regulate. The effects of production factors are distributed equally in most cases.

Table VII.5. Output Scenario Comparison based on GTAP 10 -Power Database (Social Cost of Carbon USD 36 per metric ton of CO2)

Scenario[a.]	Region	Food & Agric.	Manuf. & Transp.	Output[b.] ($ Million) Serv.	Elec. Fos.	Elec. Ren.	Trans. & Dist.	Total[4]
BAU	ROW	9,207.85	43,785.28	69,001.42	1,264.67	470.76	611.01	124,340.99
BAU	USA	1,375.26	7,507.71	21,831.70	249.54	118.54	74.57	31,157.31
BAU	World	10,583.11	51,292.99	90,833.11	1,514.21	589.29	685.58	155,498.30

Change with respect the BAU

Scenario	Region	Food & Agric.	Manuf. & Transp.	Serv.	Elec. Fos.	Elec. Ren.	Trans. & Dist.	Total
Scenario: Regulating emissions from all economic sectors								
Harmonized Policies								
$C\&T$	ROW	-1.48	-67.41	42.97	-20.05	-0.11	-0.45	-46.53
$C\&T$	USA	-2.26	5.47	2.20	-8.28	-0.22	-0.14	-3.24
$C\&T$	World	-3.74	-61.94	45.17	-28.33	-0.34	-0.59	-49.77
IS	ROW	-1.51	-68.55	43.71	-20.38	-0.12	-0.46	-47.31
IS	USA	-2.30	5.58	2.22	-8.42	-0.23	-0.15	-3.29
IS	World	-3.81	-62.98	45.93	-28.79	-0.34	-0.60	-50.60
Unilateral Policies								
$C\&T_U$	ROW	164.54	-554.68	-455.15	43.09	25.81	42.39	-734.00
$C\&T_U$	USA	9.40	32.22	-39.66	-21.64	-0.44	-0.32	-20.44
$C\&T_U$	World	173.95	-522.46	-494.81	21.45	25.37	42.07	-754.44
IS_U	ROW	164.54	-554.68	-455.15	43.09	25.81	42.39	-734.00
IS_U	USA	9.40	32.22	-39.66	-21.64	-0.44	-0.32	-20.44
IS_U	World	173.95	-522.46	-494.81	21.45	25.37	42.07	-754.44
Scenario: Regulating emissions from power generation								
Harmonized Policies								
$C\&TFOS$	ROW	-1.44	-65.69	41.88	-19.55	-0.11	-0.44	-45.35
$C\&TFOS$	USA	-2.20	5.30	2.16	-8.09	-0.22	-0.14	-3.18
$C\&TFOS$	World	-3.63	-60.39	44.04	-27.64	-0.33	-0.58	-48.53
$ISFOS$	ROW	-1.89	-82.04	52.30	-24.23	-0.14	-0.55	-56.53
$ISFOS$	USA	-2.79	6.92	2.47	-9.93	-0.27	-0.17	-3.77
$ISFOS$	World	-4.67	-75.12	54.77	-34.15	-0.41	-0.72	-60.30
Unilateral Policies								
$C\&TFOS_U$	ROW	165.01	-550.19	-457.89	43.04	25.83	42.41	-731.79
$C\&TFOS_U$	USA	8.93	30.18	-38.55	-20.90	-0.43	-0.31	-21.08
$C\&TFOS_U$	World	173.94	-520.01	-496.44	22.14	25.40	42.10	-752.88
$ISFOS_U$	ROW	165.01	-550.19	-457.89	43.04	25.83	42.41	-731.79
$ISFOS_U$	USA	8.93	30.18	-38.55	-20.90	-0.43	-0.31	-21.08
$ISFOS_U$	World	173.94	-520.01	-496.44	22.14	25.40	42.10	-752.88

a. Policy Abbreviations: BAU - Business as Usual, C&T - Cap and Trade, IS - Intensity Standard. Subscript U denotes unilateral regulations, in those cases only USA regulates emissions. Cases labeled with 'FOS' denote that the regulation was applied only to the fossil fuel electricity generation.

b. Sectors and regions abbreviations: ROW - Rest of the World, USA - United States, Food & Agric. - Food and Agriculture, Manuf. & Transp. - Manufacturing and Transportation, Serv. - Services, Elec. Fos. - Fossil power generation, Elec. Ren.- Renewable power generation, Elec. TnD. - Electricity Transmission and Distribution, NA - not available, World represents the geographic coverage in the GTAP 10 database and not necessarily means a complete representation of the globe. Total emissions might not correspond to the overall global emissions registered in 2014 but to the sectors and regions registered in the GTAP database.

Source: Own elaboration based on GTAP 10 database.

Table VII.6. Effects on Production Factors

Case[a.]	Region	Food and Agriculture Capital	Food and Agriculture Land	Food and Agriculture Skilled labor	Food and Agriculture Labor	Manufacturing and Transportation Capital	Manufacturing and Transportation Natural resources	Manufacturing and Transportation Skilled labor	Manufacturing and Transportation Labor	Services Capital	Services Skilled labor	Services Labor
BAU	ROW	1,170.930	610.195	266.671	1,190.634	6,014.433	949.233	1,425.523	1,425.523	18,155.578	7,932.808	7,147.003
BAU	USA	171.203	46.803	106.477	112.595	689.126	102.926	605.549	605.549	3,329.279	5,129.207	3,172.335
						Change with respect the BAU						
Scenario: Regulating emissions from all economic sectors												
Harmonized Policies												
$C\&T$	ROW	-0.227	0.000	-0.085	-0.192	-9.959	0.000	-2.636	-2.636	12.310	3.287	5.334
$C\&T$	USA	-0.285	0.000	-0.201	-0.213	0.693	0.000	0.403	0.403	1.475	-0.100	-0.100
IS	ROW	-0.232	0.000	-0.087	-0.196	-5.129	0.000	-2.681	-2.681	12.520	3.343	5.425
IS	USA	-0.291	0.000	-0.205	-0.217	0.706	0.000	0.412	0.412	1.497	-0.103	-0.104
Unilateral Policies												
$C\&T_U$	ROW	188.117	-0.606	54.928	198.561	-46.992	-0.962	-7.182	-7.182	-147.379	-50.060	-133.892
$C\&T_U$	USA	1.323	-0.047	0.796	0.801	3.345	-0.103	2.703	2.703	-4.157	-9.111	-7.971
IS_U	ROW	188.117	-0.606	54.928	198.561	-42.992	-0.962	-7.182	-7.182	-135.379	-50.060	-133.892
IS_U	USA	1.323	-0.047	0.796	0.801	3.345	-0.103	2.703	2.703	-4.157	-9.111	-7.971
Scenario: Regulating emissions from power generation												
Harmonized Policies												
$C\&TFOS$	ROW	-0.220	0.000	-0.083	-0.186	-9.705	0.000	-2.569	-2.569	11.997	3.204	5.198
$C\&TFOS$	USA	-0.278	0.000	-0.196	-0.207	0.673	0.000	0.391	0.391	1.442	-0.095	-0.094
$ISFOS$	ROW	-0.290	0.000	-0.107	-0.247	-12.122	0.000	-3.208	-3.208	14.978	3.999	6.498
$ISFOS$	USA	-0.353	0.000	-0.248	-0.263	-4.134	0.000	0.516	0.516	1.744	-0.145	-0.157
Unilateral Policies												
$C\&TFOS_U$	ROW	188.194	-0.606	54.949	198.633	-46.317	-0.962	-7.005	-7.005	-148.138	-50.262	-134.258
$C\&TFOS_U$	USA	1.256	-0.047	0.755	0.760	3.138	-0.103	2.525	2.525	-4.046	-8.899	-7.707
$ISFOS_U$	ROW	188.194	-0.606	54.949	198.633	-46.317	-0.962	-7.005	-7.005	-148.138	-50.262	-134.258
$ISFOS_U$	USA	1.256	-0.047	0.755	0.760	3.138	-0.103	9.525	9.525	-4.046	-8.899	-7.707

a. Policy Abbreviations: BAU - Business as Usual, C&T - Cap and Trade, IS - Intensity Standard. Subscript U denotes unilateral regulations, in those cases only USA regulates emissions. Cases labeled with 'FOS' denote that the regulation was applied only to the fossil fuel electricity generation.

Source: Own elaboration based on GTAP 10 database.

Table VII.7. Effects on Production Factors

Case[a.]	Region	Fossil Power Generation Capital	Fossil Power Generation Skilled labor	Fossil Power Generation Labor	Renewable Power Generation Capital	Renewable Power Generation Skilled labor	Renewable Power Generation Labor	Transmission and Distribution Capital	Transmission and Distribution Skilled labor	Transmission and Distribution Labor
BAU	ROW	124.295	30.263	34.533	270.604	25.922	26.481	139.550	73.281	26.481
BAU	USA	52.530	2.106	8.056	72.796	4.256	7.172	6.074	11.074	7.172
Change with respect the BAU										
Scenario: Regulating emissions from all economic sectors										
Harmonized Policies										
$C\&T$	ROW	-1.967	-0.486	-0.544	-0.061	-0.012	-0.004	-0.096	-0.068	-0.004
$C\&T$	USA	-1.740	-0.071	-0.270	-0.133	-0.010	-0.016	-0.010	-0.022	-0.016
IS	ROW	3.001	-0.494	-0.553	-0.062	-0.012	-0.004	1.902	-0.069	-0.004
IS	USA	-1.768	-0.072	-0.275	-0.135	-0.010	-0.016	-0.010	-0.023	-0.016
Unilateral Policies										
$C\&T_U$	ROW	1.234	0.273	-0.023	-15.115	-1.663	-1.945	-7.819	-4.589	-1.945
$C\&T_U$	USA	-4.547	-0.183	-0.706	-0.262	-0.017	-0.034	-0.022	-0.046	-0.034
IS_U	ROW	1.234	0.273	-0.023	-15.115	-1.663	0.055	-7.819	-4.589	0.055
IS_U	USA	-4.547	-0.183	-0.706	-0.262	-0.017	-0.034	-0.022	-0.046	-0.034
Scenario: Regulating emissions from power generation										
Harmonized Policies										
$C\&TFOS$	ROW	-1.918	-0.474	-0.531	-0.060	-0.012	-0.004	-0.094	-0.067	-0.004
$C\&TFOS$	USA	-1.699	-0.069	-0.264	-0.129	-0.009	-0.016	-0.009	-0.022	-0.016
$ISFOS$	ROW	-2.377	-0.587	-0.658	-0.072	-0.015	-0.005	-0.117	-0.083	-0.005
$ISFOS$	USA	-2.085	-0.085	-0.324	3.839	-0.012	-0.020	-0.012	-0.027	-0.020
Unilateral Policies										
$C\&TFOS_U$	ROW	1.229	0.272	-0.024	-15.107	-1.661	-1.944	-7.815	-4.586	-1.944
$C\&TFOS_U$	USA	-4.392	-0.177	-0.682	-0.256	-0.017	-0.033	-0.022	-0.045	-0.033
$ISFOS_U$	ROW	1.229	0.272	-0.024	-18.107	-1.661	-1.944	-7.815	-4.586	-1.944
$ISFOS_U$	USA	-4.392	-0.177	-0.682	1.744	-0.017	-0.033	-0.022	-0.045	-0.033

a. Policy Abbreviations: BAU - Business as Usual, C&T - Cap and Trade, IS - Intensity Standard. Subscript U denotes unilateral regulations, in those cases only USA regulates emissions. Cases labeled with 'FOS' denote that the regulation was applied only to the fossil fuel electricity generation.
Source: Own elaboration based on GTAP 10 database.

VII.4. Conclusions

The study results presented in this chapter provide further insights on the results presented in the previous chapters. Unilateral regulation will cause emissions to leak to the sectors and countries that are not regulated. The policy values are important because they show how the regulation interacts with the overall economy. The results of the GTAP model suggest important general equilibrium effects on labor and capital markets. The hypothetical case of regulating the fossil fuel industry unilaterally in the USA shows that the country that regulates will implicitly pay higher endogenous carbon prices than in the harmonized cases. Unilateral and incomplete regulation is costly in that it will lead to larger carbon endogenous prices and to the factor re-allocation of capital and labor to the unregulated industries and regions. Harmonized policies across regions and sectors are always preferred because such policies report larger overall welfare. Furthermore, the choice of the regulatory instrument determines the size of the effects. IS has proven to be a superior instrument to a C&T mechanism for incomplete and unilateral regulation cases. The conclusions presented in this chapter should be considered carefully. While the results represent the best estimates that can be made with the available tools, there may be cases like the $ISFOS_U$ where the model did not reach its maximum even with the total emission reductions. [5]

[5] For example, in the case of the IS, fossil fuel may require a parameter value greater than 100 to converge toward a maximum. Those cases are unfeasible to implement in a comparative statics model because one cannot tell exactly where the maximum is.

CHAPTER VIII

DYNAMIC CGE: EMISSIONS REGULATIONS APPLIED TO THE ELECTRICITY SECTOR

In this chapter, I present a dynamic formulation of the GTAP model (van der Mensbrugghe, 2018). The model is recursive-dynamic. The baseline is calibrated to the published forecast of GDP and population data from the International Institute for Applied Systems Analysis – Socio-Economic Pathways (Riahi et al., 2017). The process of constructing the baseline is described in detail in Britz and Roson (2019a). The simulation results mostly rely on the baseline, and so it is crucial to have a consistent baseline with the policies to be analyzed.

The primary data source utilized in this chapter is the same as the database described in Chapter VII (GTAP-Power database with the CO_2 and air pollution emissions modules). Country aggregation was performed, taking into account the classification of primary energy producers and exporters (as in Peters (2016a)) and also accounting for the fact that the regions represented in the data have a better quality of data.

This chapter's model addresses a slightly different question than the one addressed in previous chapters. This chapter will assess the effectiveness of the regulations in achieving carbon targets in the power sector by 2050. Therefore, the research question is; given the policy, what is the best regulatory instrument (in terms of maximizing overall welfare minus the global emissions multiplied by the social cost of carbon) for achieving the net-zero target for electricity generation? The model is used to compare environmental regulations in terms of the resulting economic outcomes (Real Gross Domestic Product and equivalent variation) to achieve emissions targets for power generation.

There is great interest among policymakers in what is known as the ’clean generation mix’ or ’net-zero emissions’ for electricity generation. There are multiple papers relating to the achievement of carbon targets in the future (Matthews et al., 2018). The aim of this target is for the energy mix to come entirely from renewable sources by 2050. A dynamic setting is useful in this context because it allows analysis of targets such as this. Furthermore, the harmonized cases takes into account targets set by several nations, making it a cross-country analysis.

The Intergovernmental Panel on Climate Change (IPCC) set the climate target to $1.5\,°\mathrm{C}$ and “concluded that global emissions need to reach net-zero around the mid-21st century to give a reasonable chance of limiting warming to $1.5\,°\mathrm{C}$”(Gasser and Luderer, 2018; International Carbon Action Partnership, 2020). This chapter uses a simulation exercise to examine the mid-century net-zero emissions policy in the energy sector. As in the previous chapter, emissions corresponding to extractive industries such as coal, gas, and oil are discussed. However, the regulation will only be applied to the electricity sector.

The first section of this chapter covers the aggregation of commodities and countries; the second section explains the policies represented in the chapter; the third section presents a discussion of the model, the fourth section presents the results. The last section provides a conclusion.

VIII.1. Commodity and Region Aggregation

In this chapter, energy goods are aggregated to greater detail to account for each power generating technology. Table VIII.1 presents the results of the aggregation.

The more disaggregated dataset presented in this chapter retains all regions and markets from the GTAP-Power 10 database. The accounts of *oil* (crude oil), *coal* (coal), *p_c* (petroleum and coal products), and *gas* (natural gas extraction) are presented together with a full disaggregation of the energy sector.

The variables and the notation presented in Chapter VII are valid for the discussion in the present chapter; as mentioned in Chapter VI, a significant advantage of Britz and van der Mensbrugghe (2018a) is that it created uniform notation that allows for model comparison. Table VIII.1 presents the sector and country aggregation used for the analysis.

Table VIII.1. Sector and Regions in the Aggregation Of Chapter VIII

Sectors	
Agriculture	Agriculture
Coal	Coal Mining
En_Int_Ind	Energy Intensive Industries
Gas	Natural Gas Extraction
Oil	Crude Oil
Oil_Pcts	Refined Oil Products
Oth_Ind	Other Industry
Services	Services
Electricity	
Coal	Coal (B)
Gas	Gas (BP)
Hydro	Hydro (B)
Nuclear	Nuclear (B)
Oil	Oil (BP)
Other	Other (B)
Wind	Wind (B)
Solar	Solar (P)
TnD	TnD

Regions	
CA	Central Asia
CAN	Canada
CHINA	China + HKG
EUx	European Union + others
EXAs	SE Asian Exporters
EXLA	Latin American Exporters
IND	India
JPN	Japan
MENA	Middle East and North Africa
NGA	Nigeria
RUS	Russia
USA	United States
XE	Rest of Europe
ZAF	South Africa
RoW	Rest of the World

Other includes biomass, solar thermal, geothermal, bio-gas, biomass, solid waste incineration, etc.

VIII.2. Constraints on Emissions

The constraints on emissions differ from those in the previous chapter due to the dynamics of the model. To achieve annual environmental targets, a new equilibrium is found with a proportion of emissions that have to be contributed by the end of the period when the target is achieved.

Table VIII.2 presents the constraints on emissions for the environmental targets that correspond to the illustrative calculations. In Table VIII.2, the cumulative yearly reductions represent the environmental target to get to 100% emissions reductions for 2050. Note that each period in the economy will behave differently (or not) depending on how the relative prices respond to the next period's economic conditions. Since the model is larger –relative to the model presented in the previous chapter– and includes more years, countries, and sectors than in the previous chapter, the approach is slightly different. All emissions from fossil fuel electricity generation are reduced by the end of the period (2050); in 2050, the sum of emissions from fossil fuel sources will be reduced by 100% [1].

Table VIII.2 presents similar notation as in Table VII.2. The description of the variables is presented in Table VI.2 and $emis_{BAU}$ refers to the baseline emissions. pol is a parameter that denotes the end period (100% emissions reduction from power generation) target to be distributed over the years.

[1]Because the model will not report feasible solutions for all the cases to achieve 100% emissions reductions for power generation, the feasible solution for this chapter is the one that reports the largest possible emissions reductions from power generation for each case. See Table VIII.4 for a detail of the emissions covered in the model

Table VIII.2. Implementation of Environmental Regulations in the Dynamic CGE Model

Regulating emissions from power generation	
Harmonized policies	
$C\&TFOS$	$\sum_r emis(r,fos) = \sum_r emis_{BAU}(r,fos) * \left(1 - pol * \frac{(t-1)}{(T-1)}\right)$
$ISFOS$	$\frac{\sum_r emis(r,fos)}{\sum_r xs(r,fos)} = \frac{\sum_r emis_{BAU}(r,fos)}{\sum_r xs_{BAU}(r,fos)} * \left(1 - pol * \frac{(t-1)}{(T-1)}\right)$
Unilateral policies	
$C\&TFOS_U$	$emis(USA,fos) = emis_{BAU}(USA,fos) * (1 - pol * \left(1 - pol * \frac{(t-1)}{(T-1)}\right)$
$ISFOS_U$	$\frac{emis(USA,fos)}{xs(USA,fos)} = \frac{emis_{BAU}(USA,fos)}{xs_{BAU}(USA,fos)} * (1 - pol * \left(1 - pol * \frac{(t-1)}{(T-1)}\right)$

VIII.3. Illustrative Calculations Dynamic Version

Several papers focus on emissions reduction targets that result in international cooperation agreements, such as the United Nations International Panel of Climate Change (IPCC) (European Comission, 2015). In the recent years several countries have compromised on emission reductions targets for power generation (either percentage of emissions reductions from a baseline or a limit to emissions to the country's GDP). These international agreements are sub-optimal cooperation measures to curve carbon emissions because participation is voluntary, and the targets are determined unilaterally by each country. As discussed in the previous chapters, lack of coordination does not guarantee that the countries that produce a significant quantity of emissions will participate and does not ensure that the global target is the one that maximizes overall welfare. Furthermore, countries that decide not to participate could benefit from the overall reduction of emissions without reducing emissions themselves.

The version of the model used in this chapter is called GRDEM developed by Britz and van der Mensbrugghe (2018a) [2]. The constructed model is based on CES formulations (similarly to standard GTAP) using constant returns to scale. Therefore, the total product is not defined by the model but by the cost minimization problem (Britz and Roson, 2019a). The results of this chapter are based on a Constant Demand Elasticity specification for the household demand. The representative household for each region receives income and distributes it among savings and consumption by maximizing a social welfare function. These standard assumptions can be changed in different versions of the GTAP model. There are several choices for final demand, including different specifications such as Constant Demand Elasticity (CDE), the Cobb Douglas function, linear expenditure system, the estimated modified implicit directly additive demand system (MAIDADS) with nonlinear Engel curves, or the AIDAD system (which requires parameters to be estimated econometrically) (Britz and Roson, 2019a).

More specifically, in the simulations presented in the tables below, I assess the economic impact of *unilateral* and *harmonized* regulatory policies imposed on electricity generation in the U.S. and the rest of the regions in the model. The growth variables used to develop the dynamic scenarios are GDP growth and population growth, which are exogenously imputed. The GDP and population parameters are extracted from the Shared Socioeconomic Pathways - Sustainability Scenario (Riahi et al., 2017)[3].

The main architecture of the dynamic canonical model is flexible enough

[2] To implement the simulations, I used CGEBox (Britz and Roson, 2019a)

[3] See https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=80

to accommodate a variety of cases for the analysis of environmental regulations[4] is a flexible CGE tool based on GTAP data (Britz and van der Mensbrugghe, 2018a). The model's main structure is based on a set of canonical assumptions found in various CGE models (Britz and van der Mensbrugghe, 2018a). As described in Chapter VI, these assumptions refer to competitive markets for products and factors, cost minimization for the firm with production function based on constant returns to scale, and zero profit conditions. Revenues for the firms are obtained from selling goods in the market. Households maximize utility subject to budget constraints. In addition, there is a global bank that collects savings globally and allocates investments, this is a structure that serves as a closure in most of the models (van der Mensbrugghe, 2018).

The model presented in this chapter is an adaptation of the model proposed by (Britz and Roson, 2019b); *A GTAP-Based Recursive Dynamic CGE Model for Long-Term Baseline Generation and Analysis (GRDEM)*. The selection of the model makes it possible to analyze the effects of the regulations in a recursive dynamic setting in an economy calibrated with real data. The behavioral parameters were estimated econometrically whenever possible using the techniques presented (see (Roson and Britz, 2018b) and Appendix C). GRDEM allows the calibration of different elasticity parameters and it is more flexible than the standard GTAPinGAMS version (Lanz and Rutherford, 2016) described in the previous chapter. GRDEM uses a recursive dynamic structure (2015-2050) for the long-term baseline calibration, the intertemporal equilibirum is composed of a sequence of several static equilibria. The first-year equilibrium in the sequence

[4]For a detailed specification of all the features see CGEBox documentation in `https://www.ilr.uni-bonn.de/em/rsrch/cgebox/cgebox_e.htm`

is the benchmark year. In each period, the model is solved for a different equilibrium given the parameters and equations assumed for each period (Dixon et al., 2013). For the benchmarking case, it is assumed that the economy is on a balanced growth path. In the steady-state, all quantity variables grow at the same rate, and prices remain constant.

VIII.4. Simulation Results

Since different assumptions will lead to a different equilibrium, four cases were analyzed in detail: i) harmonized C&T on emissions to power generation industries[5], $C\&TFOS$; ii) unilateral C&T system on emissions to power generation (where the United States reduces emissions for electricity generation to zero by 2050), $ISFOS$; iii) harmonized intensity standard regulation to power generation industries, $C\&TFOS_U$; and iv) unilateral intensity standard regulation to power generation industries, $ISFOS_U$.

The following Table VIII.3 shows the effects of the policies on GDP. The baseline scenario corresponds to GDP resulting from maximizing welfare minus the social cost of carbon, penalized at $36 per metric ton of CO_2, whcih is an important assumption imposed to the model. Emissions were constrained from the United States electric power generation from fossil fuels to fall by 100% gradually. In the first two cases, harmonized cases, $C\&TFOS$ and $ISFOS$, emissions are reduced the most, and we observe an overall improvement of GDP to 2050 . Furthermore, all countries and regions will grow by 2050. In the third and fourth cases, unilateral cases, $C\&TFOS_U$ and $ISFOS_U$, the regulation was

[5] The model reports feasible solution of emissions reductions in all regions up to the closest value to end period target of 100% of emissions reductions to 2050 (see Table VIII.4 for the resulting value of emissions after applying the constraints). For the subsequent scenarios, the results correspond to the case where overall emissions are reduced for electricity generation.

Table VIII.3. Real GDP Effects: Socioeconomic Pathways Sustainability Scenario

Region	**BAU**	**C&TFOS**	**ISFOS**	**C&TFOSU**	**ISFOSU**
	$ Million	% change 2050-2015	% change 2050-2015	% change 2050-2015	% change 2050-2015
Canada	1,767.48	0.71	0.78	-4.69	-3.48
Central Asia	440.63	3.15	3.09	-1.63	3.25
China + Hong Kong	10,396.78	1.34	2.00	-3.93	-3.73
European Union	19,660.90	0.40	0.16	-4.19	-4.08
India	1,981.14	3.42	3.17	-3.28	-2.21
Japan	4,566.41	0.86	0.85	-5.41	-4.95
Latin American Exporters	3,011.78	1.21	1.00	-4.55	-3.85
Middle East and North Africa	3,416.19	2.06	1.98	-4.07	-3.45
Nigeria	566.59	0.85	0.36	-4.92	-1.20
Rest of Europe	1,145.51	1.92	1.32	-5.53	-3.69
Russia	1,995.37	2.41	1.87	-3.31	-2.28
South Africa	335.90	4.96	4.19	4.79	4.50
South Asian Exporters	1,388.86	2.09	1.92	-3.43	-1.90
United States	17,207.51	0.37	0.12	-4.22	-4.10
Rest of the World	9,486.85	1.40	1.31	-1.75	0.58
Carbon Price: $/Mt.$CO_{2eq}$	0.00	72.27	70.77	100.32	101.17

The baseline GDP corresponds to 2014 GTAP values minus the social cost of carbon at $36 per metric ton (Mt.) of CO_2.

applied to the emissions from the power sector from the United States in the case of $C\&TFOS_U$ and to the ratio of domestic emissions per output $ISFOS_U$, which reduces the ratio of emissions per output from the power generation sector (See Table VIII.3). Because the emissions reduced overall are smaller in the unilateral cases, the overall growth is compromised by the drastic measure imposed by one country and one industry to reduce overall emissions from power generation unilaterally.

Table VIII.4 presents the emissions reported by the model by case after applying the constraints. Because the target is set to reduce emissions from the power generation to 2050 by 100%, the exercise can be thought of as a net-zero emissions case in the electricity sector, highlighting not the need for the right instrument to achieve that target, but more importantly, highlighting the need of coordination across regions and industries to achieve that target. All countries will reduce emissions from fossil fuels to zero in the harmonized scenarios, C&P and IS, overall welfare will improve by 2050 in all regions, and the endogenous carbons prices by 2050 would be lower as compared to the unilateral cases (see last row of Table VIII.3). Therefore, what is interesting about this exercise, besides learning which regulatory instrument performs better in achieving the highest welfare is that the question about the regulatory mechanism becomes less relevant and inconclusive because it is exogenously determined when the goal is to chieve the largest possible amount of emissions reductions. The relevant question, in this case, is about the feasibility of implementing coordinated and harmonized policies to avoid negative effects in overall welfare. Since the policy is an exogenously determined target, several economic relationships have to change to accommodate the target in terms of production, demand, and trade. Rich countries will not benefit from unilateral emissions reductions because their GDP would be penalized for the social cost of carbon to maximize overall welfare. In addition, reducing the emissions from fossil fuels in the power sector will have consequences to extractive industries that are not targeted by the regulation, such as coal mining, gas extraction, and so on.

It is interesting to note the changes in GDP to the BAU scenario in the unilateral cases. Most of the effect will reflect in the United States case of the C&T. The most significant change occurred in regions such as China, the European Union, Canada, and Latin America. The reductions in output are because achieving a clean energy mix in these countries is more costly because they have fewer possibilities for substitution.

Table VIII.4. Emissions by sector and scenario (Millions metric tons)

	Priv. cons.	**Economic Sectors**[b.]				**Energy Related Industries**[c.]				**Electricity**[d.]				
	Priv. cons.	**Agric**	**Energy** Intensive	**Other** Industry	**Serv.**	**Coal** Mining	**Crude Oil**	**Gas Extrac.**	**Oil Prod.**	**TnD**	**Coal**	**Gas**	**Oil**	**Other**
BAU[a.]														
ROW	905	42	200	155	1,196	8	35	96	103	0	1,536	522	18	1
USA	2,210	295	3,302	770	4,159	147	247	376	760	61	7,205	1,955	675	19
World	3,115	337	3,502	925	5,355	155	282	472	864	61	8,741	2,478	693	20
$C\&TFOS$[a.]														
ROW	724	37	116	119	1,172	2	5	10	52	0	77	1	0	0
USA	1,658	292	1,816	554	3,743	22	47	64	532	55	72	2	3	13
World	2,381	328	1,932	674	4,915	24	52	74	584	55	149	3	3	14
$ISFOS$[a.]														
ROW	796	40	128	131	1,289	2	5	11	57	0	84	1	0	1
USA	1,873	330	2,052	626	4,230	25	53	72	601	62	81	2	3	15
World	2,669	370	2,180	757	5,519	27	58	83	658	62	166	3	3	16
$C\&TFOS_U$[a.]														
ROW	1,086	46	240	170	1,292	8	42	106	112	0	1,689	564	22	1
USA	1,658	292	1,816	554	3,743	22	47	64	532	55	72	2	3	13
World	2,743	338	2,056	725	5,035	30	89	169	644	55	1,762	566	24	14
$ISFOS_U$[a.]														
ROW	1,411	60	312	221	1,679	11	55	137	145	0	2,196	733	28	1
USA	1,823	321	1,997	610	4,118	24	52	70	585	60	79	2	3	15
World	3,235	381	2,310	831	5,797	35	107	207	730	60	2,276	735	31	16

a. Scenario abbreviation: C&T - Cap and Trade, IS - Intensity Standard. Subscript U denotes unilateral regulations. Only USA regulates emissions in unilateral cases.
'FOS' denotes that the regulation was applied to fossil fuel electricity generation.
Economic sectors abbreviations: Agric. - Agriculture, Serv. - Services.
Energy related industries abbreviations: Gas Extrac. - Natural gas extraction, Oil Produc. - Refined Oil Products.
Electricity abbreviations: TnD - Transmission and Distribution. Other - Biomass and other renewable sources.
Other abbreviations: Priv. Cons.- Private consumption,
Nuclear, Solar, Wind, Hydro do not report emissions for the baseline.
Source: Own elaboration based on GTAP 10 database.

China was positively affected by harmonized policies. Their RGDP showed growth from 1.34% to 2.00% in the harmonized cases. The United States also obtained positive results in terms of RGDP due to the harmonized C&T implementation. Their RGDP grew by 0.37%, and in the case of the intensity standard, the effects were smaller; the RGDP growth to the BAU scenario in the United States was 0.12%. This percentages are small in terms of economic growth, however the real GDP outcome is favorable in relation to the unilateral cases, and the harmonized results are considerable because of the effects of the social cost of carbon in the overall welfare.

It is important to look at other measures, such as the equivalent variation (EV), which measure welfare changes associated with changes in prices. With income unchanged, the "change in wealth at current prices would have the same effect on consumer welfare as that of the change in prices" (Mas-Colell. et al., 1995). The changes in equivalent variations are similar to RGDP changes (see Figure VIII.1).

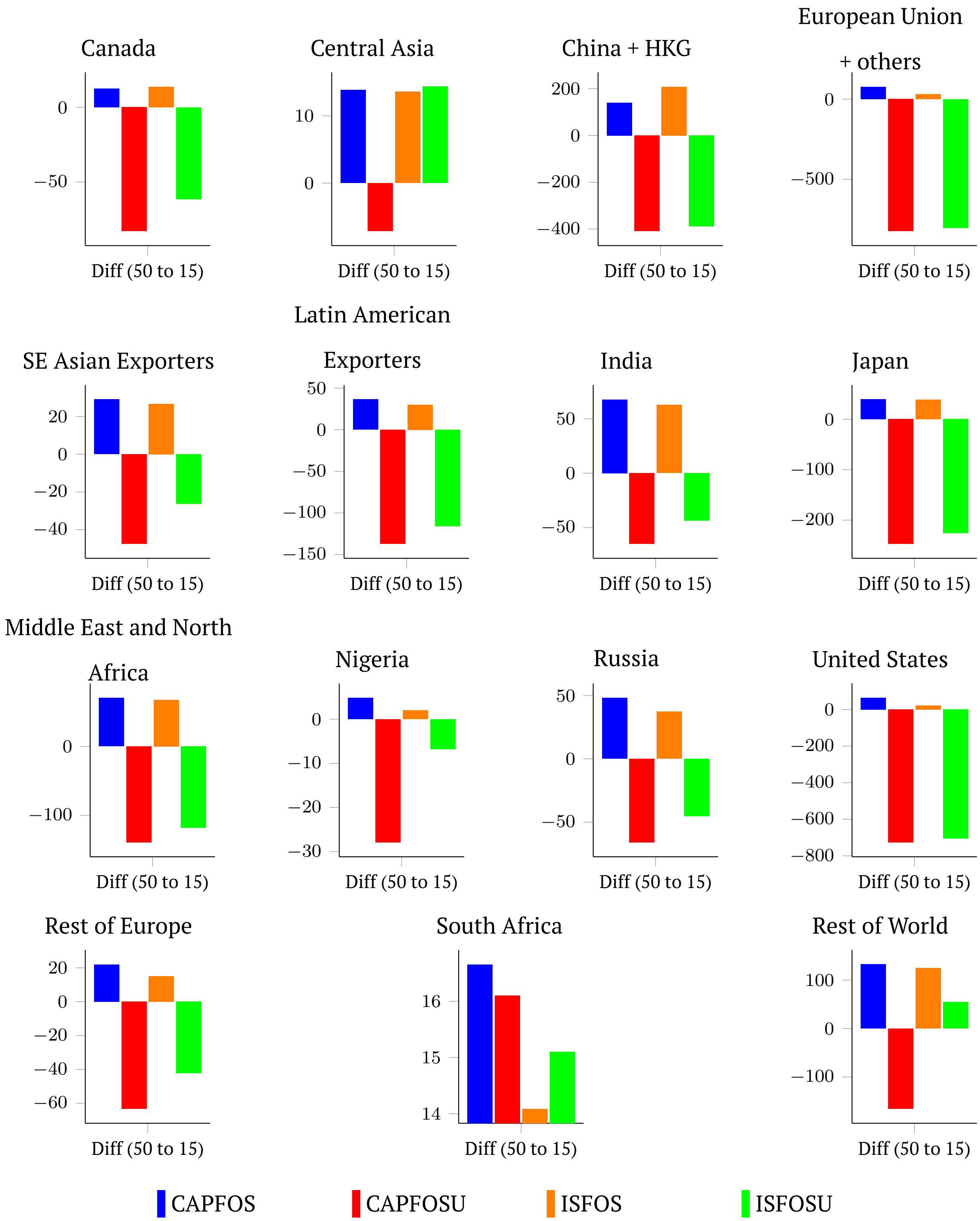


Figure VIII.1. Changes in EV wrt the baseline

The measure of equivalent variation showed a reduction of 3.84% for the

United States in the unilateral cap and trade case, and a reduction of 3.05% in the unilateral intensity standard case. China reported a reduction of 2.92% in the unilateral cap and trade case and a reduction of 2.82% in the unilateral intensity standard case. Only South Africa reported increments of RGDP and EV in all scenarios.

From the results, there is some indication that the IS unilateral regulation might be more effective in reducing the negative effects in both the power sector and the wider economy of uncoordinated policies. Leakage is lower in the intensity standard unilateral scenario because of the reduced negative effects in the United States power sector, leaving less room for countries such as China to take up the global shortfall in fossil fuel supply (see Table VIII.4). Therefore, IS may be effective in both mitigating economic losses from emissions reduction and reducing leakage to other countries. However, when the target is determined exogenously, the efficacy of the regulatory instrument can be greatly questioned. Leakage was lower in the IS scenario because it involved the targeted reduction of fossil fuel power generation (such as coal) without affecting the total United States power output.

Table VIII.5. Output ($ Million)

Case[a.]	Coal[b.]	Gas	Hydro	Nuclear	Oil	Solar	Wind	Other	TnD
BAU ROW	582.17	460.10	226.85	119.66	264.41	26.91	61.40	653.11	59.88
BAU USA	148.91	80.58	20.83	69.73	20.37	2.27	19.82	74.54	5.85
					Change with respect to BAU				
ROW									
Harmonized									
$C\&TFOS$	−576.35	−455.50	−1.00	0.25	−261.76	5.45	5.05	1.85	0.15
$ISFOS$	−564.71	−432.51	0.75	0.37	−256.47	4.17	5.12	2.18	0.19
Unilateral									
$C\&TFOS$	−147.42	−79.78	0.04	0.16	−20.17	3.80	2.00	−0.18	0.01
$ISFOS$	−148.91	−80.58	0.10	0.28	−20.37	3.90	1.78	−0.30	0.02
USA									
Harmonized									
$C\&TFOS$	−147.42	−79.78	0.04	0.16	−20.17	3.80	2.00	−0.18	0.01
$ISFOS$	−148.91	−80.58	0.10	0.28	−20.37	3.90	1.78	−0.30	0.02
Unilateral									
$C\&TFOS_U$	−110.20	−59.63	−1.57	−1.53	−4.48	14.20	2.16	−4.99	0.37
$ISFOS_U$	−101.26	−54.80	−0.62	−0.43	−3.67	15.20	1.95	−6.04	0.25

Case	Agriculture	En_Int_Ind	Oth_Ind	Services	Coal	Gas	Oil	Oil_Pcts
BAU ROW	4,173.33	15,033.02	27,694.89	68,366.35	461.93	732.83	2,152.76	3,289.99
BAU USA	404.75	1,898.56	5,487.84	21,735.23	74.24	141.57	286.91	685.08
					Change with respect to BAU			
ROW								
Harmonized								
$C\&TFOS$	0.89	−9.91	−23.13	16.82	0.92	1.85	0.29	2.41
$ISFOS$	1.23	−14.34	−46.51	18.09	0.96	1.36	2.75	4.79
Unilateral								
$C\&TFOS_U$	−222.92	4,903.21	1,727.68	−903.40	−233.96	125.70	−135.20	−223.44
$ISFOS_U$	−221.42	7,773.64	4,401.14	−905.50	−282.79	143.37	−135.15	−223.44
USA								
Harmonized								
$C\&TFOS$	0.94	2.75	−9.95	−1.04	−51.97	1.02	−1.13	2.91
$ISFOS$	0.98	4.81	−6.65	−19.65	−148.91	1.13	0.97	1.83
Unilateral								
$C\&TFOS_U$	−12.06	−96.48	−332.85	−36.10	−63.11	−120.33	−243.88	−582.32
$ISFOS_U$	−13.02	−95.18	−335.15	−38.50	−67.56	−128.83	−261.09	−623.42

a. Case abbreviations. C&T: Cap and Trade, IS: Intensity Standard, Subscript U denotes unilateral regulations. Only USA regulates emissions in those cases.
All cases labeled with 'FOS' means the regulation was only applied to the fossil fuel electricity generation industry.
b. Sectors abbreviations. En_Int_Ind: Energy Intensive Industries, Oth_Ind: Other Industries, Coal: Coal Mining, Gas: Gas Extraction, Oil: Crude Oil, Oil_Pcts: Refined Oil Products, and TnD.: Electricity: Coal, Gas, Hydro, Nuclear, Oil, Solar, Wind, Other, TnD - Transmission and Distribution.
Source: Own elaboration based on GTAP 10 database.

Changes in welfare were analyzed alongside with production and factors demands. Table VIII.5 contain illustrative results for the United States and Rest of the World. In most cases, coal electricity output decreased to null values because of regulation. In the case of harmonized policies, coal, gas, and oil reduced their usage for the production of electricity because of the regulation. The most extreme change required to achieve the net-zero target comes from coal, gas, oil sectors power generation in the United States and the Rest of the World. In the case of the United States, there was an important increment of solar power, and small increment in wind power to compensate for the changes in energy demand. These results depend on the elasticity of substitution parameters for energy goods. There is not enough flexibility in the GTAP model to substitute fossil and renewable energy, so additional assumptions for the elasticity parameters are implemented in the model to represent the electricity sector in GTAP (see Figure VI.2 in Chapter VI).

The regulation of fossil energy also affected sectors such as coal, gas, and oil. In extractive industries that are energy-intensive, the output was reduced in most of the cases (most importantly with the intensity standard case and the unilateral regulation case; see Table VIII.5). The intensity standard unilateral regulation had an effect on most variables of the economy due to the association with output. Since the carbon price is endogenous; it is not associated with a specific sector of the economy only through emissions, so the firms will not pay carbon fees directly as other factors of production, and emissions could leak to unregulated sector locally and internationally.

In terms of production factors, capital was greatly decreased in the case of the harmonized regulation in the power sector generation in the fossil fuel industry (see Table VIII.6). The results indicate that the United States and the Rest of the World would invest more capital in the fossil fuel industry only if the regulatory framework was unilateral. However, in the case of harmonized regulation, the investments in capital in fossil fuel generation are reduced significantly, mainly in the coal industry. In such cases, countries such as India and China increased capital investments in fossil fuels for electricity generation because of the implementation of unilateral policies. The model don't include any assumption about the representation of the competing costs to produce electricity by technology, which makes difficult to appropriately conclude about the future investments in fossil fuel and renewable generation. GTAP, in general, would treat the electricity sector as any other commodity, more detailed assumptions about the cost structure by technology, and assumptions about electricity generation capacity associated to different economic sector and regions, would facilitate the analysis of capital investments.

The model projects that skilled labor decreases in the electricity sector overall, but increases greatly in solar generation in the United States, especially in the case of intensity standards and unilateral regulations. This was mainly because of the output effect, since output was reduced fewer workers were needed, this is true for both skilled and unskilled labor. The reduction was much larger in the traditional fossil fuels industry than in the renewable sector. The results of changes in output and production factors are presented in Table **??** for selected sectors. Energy-intensive industries are affected by the regulation, mainly in the unilateral case.

Table VIII.6. Production Factors Electricity (Percentage Change 2050 to 2015)

Case[a.]	**Coal**[b.]	**Gas**	**Hydro**	**Nuclear**	**Oil**	**Solar**	**Wind**	**Other**	**TnD**
				Capital					
Rest of the World									
$CAPFOS$	−99.15	−96.77	0.30	0.22	−98.23	0.22	0.23	0.26	0.34
$ISFOS$	−99.45	−98.01	0.34	0.32	−99.50	0.32	0.34	0.33	0.41
$CAPFOS_U$	−18.01	−20.01	−6.71	−7.11	−20.00	−7.45	−7.23	−7.57	−6.96
$ISFOS_U$	−12.00	−12.42	−6.71	−7.11	−12.00	−7.45	−7.23	−7.57	−6.96
United States									
$C\&TFOS$	−82.57	−82.11	−1.02	0.24	−81.29	0.21	0.24	0.25	0.31
$ISFOS$	−79.04	−81.44	−3.59	0.42	−74.02	0.43	0.42	0.43	0.53
$C\&TFOS_U$	−4.43	−10.04	−8.48	0.73	−7.41	49.25	17.38	−11.69	−7.13
$ISFOS_U$	−7.30	−10.87	0.20	0.39	−12.41	98.50	22.27	−4.81	−6.27
				Skilled Labor					
Rest of the World									
$CAPFOS$	−99.98	−95.55	0.20	0.17	−99.97	0.15	0.17	0.17	0.22
$ISFOS$	−99.51	−98.00	0.19	0.20	−99.50	0.21	0.19	0.21	0.22
$CAPFOS_U$	−20.70	−20.00	−6.54	−6.88	−22.22	−6.72	−7.11	−6.99	−6.89
$ISFOS_U$	−12.01	−12.00	−6.54	−6.88	−11.01	−6.72	−7.11	−6.99	−6.89
United States									
$C\&TFOS$	−82.04	−82.00	0.16	0.17	−82.00	0.15	0.17	0.18	0.21
$ISFOS$	−82.05	−80.00	0.35	0.30	−80.00	0.29	0.30	0.30	0.37
$C\&TFOS_U$	−86.66	−5.88	−6.93	−6.38	−6.81	1,532.64	26.25	−9.68	−6.60
$ISFOS_U$	−80.59	−8.71	−6.93	−6.38	−9.61	1,277.54	28.77	−9.68	−6.60
				Unskilled Labor					
Rest of the World									
$CAPFOS$	−99.00	−96.00	0.19	0.17	−99.00	0.16	0.17	0.21	0.22
$ISFOS$	−99.50	−98.00	0.21	0.22	−99.50	0.22	0.21	0.23	0.26
$CAPFOS_U$	−20.00	−20.00	−6.37	−6.69	−20.00	−6.75	−6.92	−6.93	−6.74
$ISFOS_U$	−12.00	−12.00	−6.28	−6.69	−12.00	−6.69	−6.92	−1.57	−6.46
United States									
$C\&TFOS$	−82.00	−77.44	0.17	0.17	−82.00	0.16	0.18	0.18	0.22
$ISFOS$	−80.00	−88.17	0.35	0.30	−80.00	0.30	0.30	0.30	0.37
$C\&TFOS_U$	−4.77	−5.80	−6.81	−6.30	−6.71	−15.65	−7.04	−9.53	−6.53
$ISFOS_U$	2.15	10.48	44.66	−2.47	−9.16	−2.53	−5.41	−1.85	−6.44

a. Case abbreviations. C&T: Cap and Trade, IS: Intensity Standard, Subscript U denotes unilateral regulations. Only USA regulates emissions in those cases.
All cases labeled with 'FOS' means the regulation was only applied to the fossil fuel electricity generation industry.
b. Sectors abbreviations. En_Int_Ind: Energy Intensive Industries, Oth_Ind: Other Industries, Coal: Coal Mining, Gas: Gas Extraction, Oil: Crude Oil, Oil_Pcts: Refined Oil Products, and TnD.: Electricity: Coal, Gas, Hydro, Nuclear, Oil, Solar, Wind, Other, TnD - Transmission and Distribution.
Source: Own elaboration based on GTAP 10 database.

Table VIII.7. Production Factors Other Sectors (Percentage Change 2050 to 2015)

Case[a.]	Agriculture[b.]	En_Int_Ind	Oth_Ind	Services	Coal	Gas	Oil	Oil_Pcts
				Capital				
Rest of the World								
$CAPFOS$	0.04	−0.10	−0.08	0.02	0.08	0.00	−0.14	0.07
$ISFOS$	0.05	−0.16	−0.17	0.03	0.22	0.24	0.12	0.14
$CAPFOS_U$	−5.66	−5.23	−4.69	−4.61	−7.22	−9.31	−6.86	−6.40
$ISFOS_U$	−5.58	−5.21	−4.69	−4.61	−7.21	−9.27	−6.86	−6.23
United States								
$C\&TFOS$	0.24	0.14	−0.15	−0.01	0.23	0.51	−0.04	0.40
$ISFOS$	0.35	0.28	−0.12	−0.05	0.56	0.97	0.49	0.31
$C\&TFOS_U$	−8.04	−4.97	−6.32	−3.43	−0.87	−9.41	−8.19	−5.79
$ISFOS_U$	−7.22	0.39	−6.28	−3.42	−0.86	−9.36	−8.17	−4.12
				Skilled Labor				
Rest of the World								
$CAPFOS$	0.03	−0.12	−0.06	0.01	0.15	0.05	−0.10	0.06
$ISFOS$	0.05	−0.11	−0.10	0.01	0.23	0.17	0.12	0.10
$CAPFOS_U$	−5.77	−5.53	−5.16	−5.25	−7.04	−8.44	−7.04	−6.26
$ISFOS_U$	−5.77	−5.53	−5.16	−5.25	−7.04	−8.44	−7.04	−6.26
United States								
$C\&TFOS$	0.21	0.11	−0.08	0.00	0.20	0.43	−0.07	0.28
$ISFOS$	0.31	0.21	−0.05	−0.01	0.49	0.75	0.44	0.23
$C\&TFOS_U$	−7.66	−5.20	−6.08	−1.30	−1.53	−8.48	−7.81	−5.74
$ISFOS_U$	−7.64	−4.58	−6.03	−1.07	−1.21	−8.04	−7.56	−5.50
				Unskilled Labor				
Rest of the World								
$CAPFOS$	0.01	−0.03	−0.04	0.01	0.13	0.06	0.19	0.02
$ISFOS$	0.03	−0.05	−0.12	0.03	0.25	0.17	0.18	0.13
$CAPFOS_U$	−5.31	−5.35	−4.63	−5.35	−19.99	−8.79	−5.79	−6.55
$ISFOS_U$	−5.31	−5.35	−4.63	−5.35	−19.99	−8.79	−5.79	−6.55
United States								
$C\&TFOS$	0.22	0.11	−0.08	0.01	0.20	0.43	0.07	0.29
$ISFOS$	0.31	0.21	−0.06	0.01	0.49	0.75	0.44	0.22
$C\&TFOS_U$	−7.62	−5.13	−6.01	−1.96	−1.50	−8.43	−7.78	−5.67
$ISFOS_U$	−9.30	−5.52	−6.15	−1.58	−1.08	−8.20	−14.21	−9.47

a. Case abbreviations. C&T: Cap and Trade, IS: Intensity Standard, Subscript U denotes unilateral regulations. Only USA regulates emissions in those cases.
All cases labeled with 'FOS' means the regulation was only applied to the fossil fuel electricity generation industry.
b. Sectors abbreviations. En_Int_Ind: Energy Intensive Industries, Oth_Ind: Other Industries, Coal: Coal Mining, Gas: Gas Extraction, Oil: Crude Oil, Oil_Pcts: Refined Oil Products, and TnD.: Electricity: Coal, Gas, Hydro, Nuclear, Oil, Solar, Wind, Other, TnD - Transmission and Distribution.
Source: Own elaboration based on GTAP 10 database.

VIII.5. Conclusions

Chapter VIII presents an alternative perspective of environmental regulations analysis. In the real world, environmental targets are implemented unilaterally and by sector. Then it is enormously difficult to evaluate and determine the effects of such policies. When setting the environmental target, governments or policymakers decide on several economic variables that, in one way or another, will interact with those targets in a dynamic setting.

Another critical point is the maturity of the industries that are expected to substitute the polluting industries. When setting environmental targets in power generation, there is great expectation that the renewables will fill in the gaps left by the polluting sectors. This is not necessarily the case, more traditional technologies have competitive advantage in terms of readiness to respond to an increased demand for electricity, for example, natural gas would replace coal power plants and not necessarily wind turbine. General equilibrium dynamic effects are usually ignored, if the clean sector is not competitive, the preferred option is to reduce the demand for even renewable technologies and substitute consumption with imported products regardless of their environmental quality. The local economy can be significantly affected by the lack of coordination of environmental targets with other countries and sectors.

About the comparison of regulatory instruments, the results indicate a slightly better scenario for the Intensity Standards because the effects on output, labor, and capital are not as severe as in the Cap and Trade scenarios. Still, the results are inconclusive because there are so many intervening factors. When the target is determined exogenously, the questions shift significantly to the importance of coordinated policies and not too much about the regulatory instrument because C&T and IS can be equivalent depending on the policy's value, as seen in the previous chapters. The results presented in this chapter indicate what could happen in the economy if certain conditions are imposed. The most critical assumption is that the current and future economic conditions and technologies are appropriately represented, the results rely significantly on the elasticity of substitution between fossil fuels and renewable industries not only for power generation but for all sectors that consume electricity as an input. Suppose the same value of elasticity of substitution is applied to the entire electricity generation sectors. In that case, the industry's substitution effects will become less relevant, and the effects across industries will become more relevant. Another limitation for the analysis is that the model presented in this chapter treats electricity as any other commodity, and then doesn't include modules for capacity expansion or electricity dispatch. The model doesn't consider the possibility of carbon offsets due to technological improvements or new technologies for carbon capturing.

CHAPTER IX

CONCLUSIONS

In this dissertation I explored the general equilibrium effects of environmental regulations, comparing two polices, cap and trade and intensity standards. The objective was to evaluate the efficacy of such policies in terms of maximizing overall welfare.

In Chapter IV, I presented the theory behind a simple general equilibrium model for simplifying the comparison of environmental policies. The model in Chapter IV describes the cap and trade regulatory mechanism and the emissions per output regulatory mechanism through simple economic relationships, in great detail. The main objective is to analyze whether under leakage, one regulation performs better in terms of maximizing overall welfare. I conclude that under certain conditions – the separability of inputs in a concave production function and emissions leakage – the optimal policy should regulate emissions per unit of output as opposed to imposing a cap on emissions. Applying the main model of this dissertation, unilateral cap and trade policies are not able to replicate the first best, and more importantly, they can be an inferior instrument for regulating emissions than a unilateral intensity standard policy. This finding might explain why local policies that regulate emissions per output remain in place when there is leakage and a lack of coordination among agents. More notably, the results of Chapter V, show that the superiority of the cap and trade mechanism, relative to intensity standards previously established in the literature is confirmed only for the value of the policy that maximizes overall welfare. It is entirely possible, that the policy value target is set to any other value if determined exogenously. The latter emphasizes the importance of the choice of the target and the need for the implementation of coordinated approaches.

Chapter VII and VIII presented illustrative calculations based on GTAP data. In Chapter VII, the results reveal important general equilibrium effects on the endogenous variables of interest for the analysis, such as carbon price, emissions reductions, and effects on labor and capital markets. The hypothetical case of reducing emissions unilaterally in the U.S. indicates that country that engages in regulation would implicitly pay higher endogenous carbon prices than in the harmonized cases. Unilateral and incomplete regulation is costly, both in terms of facing larger carbon endogenous prices and in terms of factor reallocation of capital and labor to unregulated industries and regions. Harmonization of policies is always preferred as such policies elicit larger overall welfare. Furthermore, the choice of regulatory instrument is directly correlated to the size of the effects. Intensity standards have proven to be superior to cap and trade for incomplete and unilateral regulation cases.

Chapter VIII presented an alternative perspective of the analysis of the environmental regulations. In the real world, it is common to encounter environmental targets being implemented unilaterally and by sector. When setting environmental targets exogenously, there is great expectation that the clean industries will fill the gaps created by the more polluting sectors, but general equilibrium effects are ignored. If the clean sector is not competitive, the preferred option is to reduce the demand for clean goods and to substitute consumption with imported products, regardless of their environmental quality. Local economies, can be significantly affected by a lack of coordination of environmental targets with other countries or sectors. Regarding the efficacy of establishing environmental targets, the results indicate a better scenario for the intensity standards because the effects on output, labor, and capital are not as severe as in the cap and trade scenarios. Nevertheless, the results are inconclusive, as there are numerous intervening factors. One critical assumption in Chapter VII and Chapter VIII is that technological substitution is adequately represented for fossil fuel and renewables. The results rely significantly on the elasticity of substitution between fossil fuels and renewables not only for power generation but for all economic sectors that consume capital, labor, and electricity as inputs.

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APPENDIX A

A THEORETICAL MODEL OF EMISSIONS TRADING AND INTENSITY STANDARDS

Proofs of Lemmas and Propositions

Proof of Lemma 1

The BAU equilibrium is characterized by the optimization in equation (2).

The proof of lemma 1 consists in exploring if solving the welfare maximization function in equation (A1) yields the same results as solving the system of equations consisting of the FOCs from the consumer and producer problems (A2) and (A4). If this is the case, the BAU equilibrium is characterized by this optimization. The following maximization program defines the Lagrangian function of equation (2).

$$\max_{q_{ic}^D, K_{ic}, L_{ic}} \sum_c U_c(q_{1c}^D, q_{2c}^D) + \lambda_K \left(\overline{K} - \sum_c \sum_i K_{ic} \right) + \sum_c \lambda_{L_c} \left(\overline{L}_c - \sum_i L_{ic} \right) + \sum_i \lambda_{q_i} \sum_c \left(q_{ic} \left(K_{ic},\ L_{ic} \right) - q_{ic}^D \right) \qquad \forall i, c. \quad \text{(A1)}$$

Solving the consumer and producer problems yields the same FOCs as solving the problem in equation (2), where μ_U is the multiplier associated with the income constraint.

Consumer problem:

$$\max_{q_{1c}^D, q_{2c}^D} \sum_c U_c\left(q_{1c}^D,\ q_{2c}^D\right) + \mu_U\left(I - \sum_i P_i q_{ic}^D\right) \qquad \forall i, c \tag{A2}$$

Combining the FOCs for q_{1c}^D and q_{2c}^D, the MRS is:

$$\frac{\partial U_c/\partial q_{1c}^D}{\partial U_c/\partial q_{2c}^D} = \frac{P_1}{P_2} \qquad \forall c \tag{A3}$$

Equation (A3) is equivalent to equation (6) because the shadow prices in equation (3) represent the actual prices of *Good 1* and *Good 2*.

Producer problem:

$$\max_{K_{ic},\ L_{ic}} \sum_c P_i q_{ic}\left(K_{ic},\ L_{ic}\right) - w_c L_{ic} - rK_{ic} \qquad \forall i, c \tag{A4}$$

The FOCs are:

$$\frac{\partial q_{ic}(K_{ic}, L_{ic})}{\partial K_{ic}} = \frac{r}{P_i} \qquad \forall i, c \tag{A5}$$

$$\frac{\partial q_{ic}(K_{ic}, L_{ic})}{\partial L_{ic}} = \frac{w_c}{P_i} \qquad \forall i, c \tag{A6}$$

Equations (A5) and (A6) are equivalent to equations (4) and (5), the shadow prices in equations (4) and (5) represent the actual prices of capital and labor for the production of *Good 1* and *Good 2*.

Proof of Lemma 2

The harmonized C&T equilibrium is characterized by the optimization in equation (12).

To show that there is a solution to the harmonized C&T scenario the Lagrangian function is defined as equation (A7):

$$\max_{q_{ic}^D, K_{ic}, L_{ic}} \sum_c U_c(q_{1c}^D, q_{2c}^D) + \lambda_K(\overline{K} - \sum_c \sum_i K_{ic}) + \sum_c \lambda_{L_c}(\overline{L}_c - \sum_i L_{ic})$$
$$+ \sum_i \lambda_{q_i} \sum_c (q_{ic}(K_{ic},\ L_{ic}) - q_{ic}^D) + \lambda_e(\overline{e} - e_2(K_{2A},\ L_{2A} + e_2(K_{2B},\ L_{2B})) \qquad \forall i, c \tag{A7}$$

By solving the consumer and producer problems, the same solution as the BAU case is found for *Country B*. For *Country A*, the profit maximizing condition for *Good 2* changes slightly to the following:

$$\max_{K_{2c},\ L_{2c},} \ P_2 q_{2c}(K_{2c},\ L_{2c}) - \ w_c L_{2c} - rK_{2c} \ - \lambda_e e_{2c}(K_{2c}, L_{2c}) \qquad \forall c \tag{A8}$$

The FOC with respect to K_{2A} and L_{2A} changes to the following:

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial K_{2c}} = \frac{r}{P_2} + \frac{\lambda_e}{P_2}\frac{\partial e_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial K_{2c}} \qquad \forall c \qquad \text{(A9)}$$

$$\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial L_{2c}} = \frac{w_c}{P_2} + \frac{\lambda_e}{P_2}\frac{\partial e_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial L_{2c}} \qquad \forall c \qquad \text{(A10)}$$

where P_2 in equations (A9) and (A10) is equivalent to λ_{q_2} in equations (13) and (14).

Proof of Lemma 3

The unilateral C&T equilibrium is characterized by the optimization in equation (16).

The solution to the unilateral C&T scenario is the Lagrangian function defined in equation (A11). The solution of the BAU case applies to *Country B* in the unilateral C&T case. For *Country A*:

$$\max_{q_{ic}^D, K_{ic}, L_{ic}} \sum_c U_c(q_{1c}^D, q_{2c}^D) + \lambda_K(\overline{K} - \sum_c \sum_i K_{ic}) + \sum_c \lambda_{L_c}(\overline{L}_c - \sum_i L_{ic})$$
$$+ \sum_i \lambda_{q_i} \sum_c \left(q_{ic}\left(K_{ic},\ L_{ic}\right) - q_{ic}^D\right) + \lambda_{eA}\left(\overline{e}_{2A} - e_2(K_{2A},\ L_{2A})\right) \qquad \forall i, c. \quad \text{(A11)}$$

On the other hand, by solving the consumer and producer problems, the same solution as that of the BAU case is found for *Country B*.

For *Country A*, the profit maximizing condition for *Good 2* changes slightly to the following:

$$\max_{K_{2A},\ L_{2A},} \ P_2 q_{2A}\left(K_{2A},\ L_{2A}\right) - \ w_A L_{2A} - r K_{2A} \ - \lambda_{eA} e_2(K_{2A}, L_{2A}) \tag{A12}$$

The FOC with respect to K_{2A} and L_{2A} changes to the following:

$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial K_{2A}} = \frac{r}{P_2} + \frac{\lambda_{eA}}{P_2}\frac{\partial e_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial K_{2A}} \tag{A13}$$

$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial L_{2A}} = \frac{w_A}{P_2} + \frac{\lambda_{eA}}{P_2}\frac{\partial e_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial L_{2A}}, \tag{A14}$$

where P_2, r, and w_A in equation (A13) and (A14) are equivalent to λ_{q_2}, λ_K, and λ_{L_A} in equations (17) and (18).

Proof of Proposition 2

The harmonized C&T equilibrium can attain the first best. The unilateral C&T equilibrium cannot attain first best due to leakage.

In equation (A13) and (A14) I obtained a solution where only *Country A* regulates emissions. The total emissions in this case is $e_A\left(K_{2A}^*,\ L_{2A}^*\right) + e_B\left(K_{2B},\ L_{2B}\right)$, where the values of K_{2B} and L_{2B} correspond to the BAU values and are not set to the optimal levels. Therefore, unilateral regulation cannot necessarily attain the first best even when regulating with the cap and trade mechanism. In this case the total amount of emissions is larger than in the first best case. See Table V.5

Proof of Lemma 4

The harmonized IS equilibrium is characterized by the optimization in equation (20).

The Lagrangian function of the harmonized IS case is defined in equation $(\mathrm{A}15)$. The solution of BAU applies to *Country B* in the *IS* case.

$$\max_{q_{ic}^{D},\ K_{ic}, L_{ic}} \sum_{c} U_c\left(q_{1c}^{D},\ q_{2c}^{D}\right) + \lambda_K\left(\overline{K} - \sum_{c}\sum_{i} K_{ic}\right)$$
$$+\sum_{c}\lambda_{L_c}\left(\overline{L}_c - \sum_{i} L_{ic}\right) + \sum_{i}\lambda_{q_{ic}}\sum_{c}\left(q_{ic}\left(K_{ic},\ L_{ic}\right) - q_{ic}^{D}\right)$$
$$+\lambda_e\left(IS\left(q_{2A}\left(K_{2A}, L_{2A}\right) + q_{2B}\left(K_{2B}, L_{2B}\right)\right) - e_{2A}\left(K_{2A},\ L_{2A}\right) - e_{2B}\left(K_{2B},\ L_{2B}\right)\right) \qquad \forall i, c. \tag{A15}$$

The FOCs of the maximization problem for *Country A* are the same as equations (21) and (22).

Similar to the previous case, the consumer and producer problems yield the same solution as the BAU case for *Country B*. For *Country A*, the profit maximizing condition for *Good 2* changes to the following:

Producer problem for good 2:

$$\max_{K_{2c},\, L_{2c}} \; P_2 q_{2c}\left(K_{2c}, L_{2c}\right) - w_c L_{2c} - r K_{2c} - \mu_e \left(e_{2c}(K_{2c}, L_{2c}) - IS_c q_{2c}\left(K_{2c}, L_{2c}\right)\right) \qquad \forall c. \tag{A16}$$

In country *c*, the producer problem of *Good 2* with respect of K_{2c} and L_{2c} yields the following:

$$\frac{\partial q_{2c}\left(K_{2c},\; L_{2c}\right)}{\partial K_{2c}} = \frac{1}{P_2 + \mu_e IS_c}\left(r + \mu_e \frac{\partial e_{2c}\left(K_{2c},\; L_{2c}\right)}{\partial K_{2c}}\right) \qquad \forall c \tag{A17}$$

$$\frac{\partial q_{2c}\left(K_{2c},\; L_{2c}\right)}{\partial L_{2c}} = \frac{1}{P_2 + \mu_e IS_c}\left(w_c + \mu_e \frac{\partial e_{2c}\left(K_{2c},\; L_{2c}\right)}{\partial L_{2c}}\right) \qquad \forall c, \tag{A18}$$

where P_2, r, w_c, and μ_e in equation (A17) and (19) are equivalent to λ_{q_2}, λ_K, λ_{L_c}, and λ_e in equation (21) and (22), respectively.

Proof of Lemma 5

The unilateral IS equilibrium is characterized by the optimization in equation (23).

The Lagrangian function of the unilateral IS case is defined in equation $(\mathrm{A}24)$. This is similar to the harmonized case above, but emissions in *Country B* are not constrained. The solution of the BAU case applies to *Country B* in the unilateral *IS* case. See equations (3) to (11).

$$\max_{q_{ic}^{D},\ K_{ic}, L_{ic}} \sum_{c} U_c\left(q_{1c}^{D},\ q_{2c}^{D}\right) + \lambda_K\left(\overline{K} - \sum_{c}\sum_{i} K_{ic}\right) + \sum_{c}\lambda_{L_c}\left(\overline{L}_c - \sum_{i} L_{ic}\right)$$
$$+\sum_{i}\lambda_{q_{i_c}}\sum_{c}\left(f_{ic}\left(K_{ic},\ L_{ic}\right) - q_{ic}^{D}\right) + \lambda_e\left(IS_{2A}q_{2A}\left(K_{2A}, L_{2A}\right) - e_{2A}\left(K_{2A},\ L_{2A}\right)\right) \qquad \forall i, c \tag{A19}$$

The FOCs of the maximization problem for *Country A* are the same as equations (3) to (10). The main difference is the derivatives with respect to K_{2A} and L_{2A} of the production function of *Country A*.

Similar to the unilateral C&T case, the consumer and producer problems will yield the same solution as the BAU case for *Country B*. For *Country A*, the profit maximizing condition for *Good 2* changes to the following:

Producer problem for good 2:

$$\max_{K_{2A},\ L_{2A}} P_2 q_{2A}\left(K_{2A},\ L_{2A}\right) - w_A L_{2A} - rK_{2A} - \mu_e A\left(IS_A q\left(K_{2A},\ L_{2A}\right) - e_{2A}(K_{2A}, L_{2A})\right) \tag{A20}$$

In *Country A*, the maximization of the production function of *Good 2* with respect to K_{2A} and L_{2A} yields the following:

$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial K_{2A}} = \frac{1}{\left(P_2 + \mu_{eA} IS_A\right)}\left(r + \mu_{eA}\frac{\partial e_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial K_{2A}}\right) \tag{A21}$$
$$\frac{\partial q_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial L_{2A}} = \frac{1}{\left(P_2 + \mu_{eA} IS_A\right)}\left(w_c + \mu_{eA}\frac{\partial e_{2A}\left(K_{2A},\ L_{2A}\right)}{\partial L_{2A}}\right), \tag{A22}$$

where P_2, μ_{eA}, r, and w_A in equations (A21) and (A22) are equivalent to λ_{q_2}, λ_{eA}, λ_K, and λ_{L_A} in equations (24) and (25), respectively.

Proof of Proposition 3

The harmonized IS equilibrium cannot attain the first best, and the unilateral C&T equilibrium cannot attain first best.

The Lagrangian function is defined as the problem presented in equation (A23). For both countries:

$$\max_{q_{ic}^D, K_{ic}, L_{ic}} \sum_c U_c(q_{1c}^D, q_{2c}^D) - \sum_c D\left(IS_c q_{2c}\left(K_{2c}, L_{2c}\right) - e_{2c}\left(K_{2c},\ L_{2c}\right)\right)$$
$$+ \lambda_K\left(\overline{K} - \sum_c\sum_i K_{ic}\right) + \sum_c \lambda_{L_c}\left(\overline{L}_c - \sum_i L_{ic}\right)$$
$$+ \sum_i \lambda_{q_{ic}} \sum_c \left(q_{ic}\left(K_{ic},\ L_{ic}\right) - q_{ic}^D\right) \qquad \forall i, c \quad \text{(A23)}$$

From the FOCs of K_{2c} and L_{2c}, I have:

$$IS_c = \frac{\lambda_K}{D} - \frac{\lambda_{q2}}{D}\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial K_{2c}} + \frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial K_{2c}} \qquad \forall c \qquad \text{(A24)}$$
$$IS_c = \frac{\lambda_{L_c}}{D} - \frac{\lambda_{q2}}{D}\frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial L_{2c}} + \frac{\partial q_{2c}\left(K_{2c},\ L_{2c}\right)}{\partial L_{2c}} \qquad \forall c \qquad \text{(A25)}$$

The values of K_{2c}^* and L_{2c}^* are the solutions of the system of equations above. The optimal IS_c ratio is set to $IS_c = \frac{e\left(K_{2c}^*, L_{2c}^*\right)}{q_{2c}\left(K_{2c}^*, L_{2c}^*\right)}$, which is the emissions function and the production function of *Good 2* evaluated at the optimal values. The total damage of emissions is $D\sum_c IS_c q_{2c}(K^*_{2c},\ L^*_{2c})$, and the damage of emissions is larger than $D\sum_c e_c(K^*_{2c},\ L^*_{2c})$.

Proof of Proposition 4

If $\sum_c U_c(q^D_{1c},\ q^D_{2c})$ is globally concave, then an equilibrium allocation exists for the BAU, C&T, and IS cases. If strictly, then unique.

$\sum_c U_c\left(q^D_{Ac},\ q^D_{Bc}\right)$ is continuous because it is the summation of two continuous functions. The domain of $U_c\left(q^D_{Ac}, q^D_{Bc}\right)$ is a compact subset. Because q^D_{ic} is contained in an interval, the lower bound of the interval is zero, and the upper bound is $q^D_{ic}(\overline{K}, \overline{L})$. Thus, q^D_{ic} is a compact set, closed and bounded. Therefore, the solution of (1) exits as a global max of U_c in its domain, by the Weierstrass theorem (Theorem 30.1 in (Simon and Blume, 1994, p. 823)).

I cannot obtain an explicit solution for the optimal values of capital and labor, and the solution will depend on the parameters and functional form assumed for the utility function and the production function.

The solution to the harmonized C&T scenario is given by the system of equations above in equations (A9) and (A10), and the solution to the harmonized IS case is given by (A13) and (A14). For the unilateral case, the solution for the C&T scenario is given by equations (A17) and (A18), and for the unilateral IS case by equations (A21) and (A22).

I will have to compare the overall welfare function evaluated at the optimal values of the variables to conclude about which regulatory mechanism is superior. I will utilize numerical methods in Chapter V to perform a comparison across cases presented in Chapter IV.

MATLAB Code for Chapter IV

Available to download at:

\url{https://colab.research.google.com/drive/

1FQ0Qv2aYooKwJ8Kf5lPEwbltOu6ZmwDa?authuser=1#scrollTo=IpEDGVwO3yPV}

APPENDIX B

HARMONIZED AND UNILATERAL POLICIES: ILLUSTRATIVE CALCULATIONS FROM THE CANONICAL MODEL

Sector in GTAP-Power

Table B.1. Definitions of sectors in GTAP 10 Power Database.

Sector	Description	Sector	Description
Agriculture and Forestry		**Energy-Intensive Industries**	
pdr	Paddy rice	gdt	Gas manufacture, distribution
wht	Wheat	p_c	Petroleum, coal products
gro	Cereal grains nec	chm	Chemical products
bph	Basic pharmaceuticals	rpp	Rubber and plastic products
v_f	Vegetables, fruit, nuts	nmm	Mineral products nec
osd	Oil seeds	i_s	Ferrous metals
c_b	Sugar cane, sugar beet	nfm	Metals nec
pfb	Plant-based fibers	fmp	Metal products
ocr	Crops nec	mvh	Motor vehicles and parts
ctl	Cattle, sheep, goats, horses	otn	Transport equipment nec
oap	Animal products nec	ele	Electronic equipment
rmk	Raw milk	eeq	Electrical equipment
ome	Machinery and equipment	afs	Accommodation and food services
whs	Warehousing and support activities	rsa	Real estate activities
wol	Wool, silk-worm cocoons	omf	Manufactures nec
edu	Education, silk-worm cocoons	hht	Human health and social work
frs	Forestry	**Energy Use**	
fsh	Fishing	coa	Coal
Other Industries		oil	Oil
omn	Minerals nec	gas	Gas
cmt	Meat: cattle, sheep, goats, horse	**Electricity**	
omt	Meat products nec	TnD	Transmission and distribution
vol	Vegetable oils and fats	NuclearBL	Nuclear base load
mil	Dairy products	CoalBL	Coal base load
pcr	Processed rice	GasBL	Gas base load
sgr	Sugar	WindBL	Wind base load
ofd	Food products nec	HydroBL	Hydro base load
b_t	Beverages and tobacco products	OilBL	Oil base load
tex	Textiles	OtherBL	Other base load
wap	Wearing apparel	GasP	Gas peak load
lea	Leather products	HydroP	Hydro peak load
lum	Wood products	OilP	Oil peak load
ppp	Paper products, publishing	SolarP	Solar peak load

Own elaboration based on GTAP database.

APPENDIX C

DYNAMIC CGE

Table C.1. Main characteristics of the baseline

Variable	All sectors	Economic sectors				Energy related sectors				Electrical power generation								
Variable	All sectors	Agriculture	Energy Intensitive Industries	Other Industry	Services	Coal Mining	Crude Oil	Natural Gas Extraction	Refined Oil Products	Coal	Gas	Hydro	Nuclear	Oil	Solar	Wind	Other	TnD
Rest of the World																		
Output	122,743.6	4,177.5	14,963.0	27,536.2	67,174.9	457.0	2,081.3	718.4	3,215.6	570.4	448.5	223.7	122.9	262.5	27.3	61.6	59.5	643.5
Intermediate demand	67,534.2	1,628.1	10,881.7	19,827.2	29,744.9	188.8	484.0	247.6	2,988.6	422.7	381.9	57.9	47.8	229.1	8.6	20.3	30.7	344.3
Intermediate input taxes	2,280.6	-6.8	463.7	486.5	1,246.1	4.5	7.6	2.2	6.1	17.8	29.0	1.2	0.5	13.1	0.0	0.2	1.5	7.3
Factor taxes	5,188.7	-0.3	287.1	730.6	4,025.1	9.2	51.5	19.6	12.8	5.3	2.7	6.6	7.2	1.9	0.9	2.2	2.0	24.2
Factor demand	48,459.2	2,557.8	3,347.5	6,532.3	32,761.0	260.9	1,551.4	454.6	225.8	132.8	41.0	158.5	63.1	18.8	17.7	38.7	25.5	271.9
Intermediate demand	67,534.2	1,628.1	10,881.7	19,827.2	29,744.9	188.8	484.0	247.6	2,988.6	422.7	381.9	57.9	47.8	229.1	8.6	20.3	30.7	344.3
Agriculture	2,692.9	442.4	57.1	1,910.2	280.2	0.9	0.2	0.4	0.3	0.2	0.0	0.2	0.1	0.1	0.0	0.0	0.1	0.6
Energy Intensitive Industries	13,686.6	208.7	6,145.0	3,683.8	3,386.1	41.1	65.9	16.2	45.5	14.9	3.0	8.4	11.2	2.8	1.0	2.8	5.3	44.8
Other Industry	15,767.2	403.3	1,001.5	9,052.5	5,023.7	38.7	108.3	42.8	18.2	14.2	2.9	7.7	6.5	2.5	1.0	3.4	2.9	37.3
Services	27,522.5	409.0	2,296.2	4,701.0	19,146.8	86.1	264.7	128.9	107.9	58.6	21.4	30.6	22.2	14.1	5.8	11.2	12.3	205.7
Coal Mining	480.8	1.5	71.1	11.7	9.4	3.8	0.0	1.7	96.3	285.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Crude Oil	2,027.7	0.0	6.4	0.6	0.4	0.0	5.3	1.7	1,987.0	0.0	0.0	0.0	0.0	26.2	0.0	0.0	0.0	0.0
Natural Gas Extraction	712.5	2.8	126.4	46.5	66.2	0.0	19.9	38.4	94.1	0.0	318.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refined Oil Products	2,820.9	85.6	604.0	60.3	1,228.9	5.4	8.1	6.3	595.2	2.5	19.4	0.0	0.0	179.3	0.0	0.0	8.6	17.2
TnD	488.6	19.4	157.4	98.1	157.1	3.7	2.9	2.8	11.8	13.1	4.0	3.1	2.0	1.0	0.2	0.8	0.4	10.8
Nuclear (B)	86.1	2.7	23.4	17.2	32.9	0.5	0.3	0.3	1.9	1.6	0.9	0.6	1.7	0.2	0.1	0.2	0.2	1.6
Coal (B)	459.3	23.8	162.8	92.4	122.7	4.8	2.0	2.1	10.5	19.5	3.0	3.0	1.5	0.8	0.2	0.8	0.3	9.0
Gas (BP)	329.8	11.2	91.3	63.8	126.6	1.2	3.6	3.6	9.2	4.0	5.3	1.0	0.9	0.7	0.1	0.3	0.2	6.8
Wind (B)	45.4	1.9	13.1	9.1	16.2	0.3	0.1	0.2	1.1	1.2	0.4	0.3	0.3	0.1	0.0	0.2	0.1	0.8
Hydro (B)	167.6	5.9	57.7	33.3	53.1	1.2	1.3	1.1	3.3	3.7	1.1	1.8	0.6	0.3	0.1	0.2	0.1	2.9
Oil (BP)	181.8	8.4	49.7	33.1	70.7	0.7	1.0	0.9	4.6	2.9	1.7	0.9	0.4	0.8	0.1	0.2	0.1	5.7
Other (B)	44.0	1.0	12.9	9.5	15.9	0.2	0.2	0.3	1.2	0.7	0.4	0.3	0.3	0.1	0.0	0.1	0.1	0.8
Solar (P)	20.5	0.5	5.6	4.1	8.1	0.1	0.0	0.1	0.5	0.4	0.2	0.1	0.1	0.1	0.0	0.1	0.0	0.3
Land	609.6	609.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Capital	25,845.9	618.0	1,971.3	3,423.7	17,912.7	87.1	884.3	258.9	177.2	85.7	31.9	139.5	47.0	8.9	15.9	31.9	20.5	131.5
NatlRes	948.3	109.0	68.6	0.0	0.0	106.6	533.1	131.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SkLab	9,745.6	92.2	428.6	1,113.5	7,861.4	12.7	65.5	31.9	16.0	22.3	3.6	7.7	9.7	5.1	0.8	4.0	2.0	68.6
UnSkLab	11,309.9	1,129.0	879.0	1,995.2	6,986.9	54.6	68.4	32.8	32.7	24.8	5.5	11.3	6.4	4.7	0.9	2.8	3.0	71.8
USA																		
Output	31,128.1	404.4	1,896.9	5,482.9	21,714.3	74.2	286.7	141.5	684.7	148.8	80.5	20.8	69.6	20.4	2.3	19.8	5.8	74.5
Intermediate demand	14,123.3	246.8	1,172.8	3,527.8	8,138.0	33.5	70.9	62.7	630.6	88.4	61.0	2.7	23.8	17.6	0.4	5.5	1.9	39.0
Intermediate input taxes	195.1	-3.7	17.3	19.5	158.0	0.3	0.5	0.2	0.3	0.4	1.2	0.0	0.2	0.6	0.0	0.0	0.0	0.2
Factor taxes	1,520.2	-9.1	64.7	186.1	1,250.0	1.9	9.6	4.0	2.7	2.6	0.6	0.7	2.7	0.1	-0.7	0.7	0.2	3.2
Factor demand	14,570.4	169.1	625.1	1,709.0	11,566.1	32.0	192.6	69.0	33.4	49.2	11.6	16.8	47.3	1.6	2.5	13.7	3.7	27.8
Intermediate demand	14,123.3	246.8	1,172.8	3,527.8	8,138.0	33.5	70.9	62.7	630.6	88.4	61.0	2.7	23.8	17.6	0.4	5.5	1.9	39.0
Agriculture	294.9	39.1	1.9	224.5	29.4	0.0	0.0	0.0					0.0		0.0			
Energy Intensitive Industries	1,601.1	20.5	538.0	607.5	409.0	6.4	9.9	2.0	5.3	0.6	0.2	0.0	0.5	0.1	0.0	0.1	0.0	0.8
Other Industry	3,131.0	61.1	134.9	1,524.2	1,390.0	7.9	5.9	2.0	1.1	1.0	0.3	0.1	0.9	0.1	0.0	0.2	0.0	1.3
Services	7,652.6	110.4	376.8	1,112.0	5,820.3	16.3	48.5	45.8	38.7	19.4	5.1	1.3	17.7	1.8	0.3	4.2	0.9	33.2
Coal Mining	63.1		1.5	1.0	0.1	0.0		0.3	2.0	58.1								
Crude Oil	518.6		0.0				0.0	0.2	518.4					0.0				
Natural Gas Extraction	124.8	0.3	19.2	9.7	21.3	0.0	3.1	7.6	20.2		43.4							
Refined Oil Products	441.3	12.4	58.5	4.8	298.3	1.7	2.0	2.8	38.5		6.5			15.2			0.7	0.0
TnD	50.1	0.5	7.1	7.5	28.7	0.2	0.2	0.3	1.1	1.6	1.0	0.2	0.8	0.1	0.0	0.2	0.1	0.6
Nuclear (B)	46.4	0.5	6.6	6.9	26.6	0.2	0.2	0.3	1.0	1.5	0.9	0.2	0.7	0.1	0.0	0.2	0.0	0.6
Coal (B)	98.9	1.0	14.0	14.7	56.7	0.4	0.5	0.7	2.2	3.1	1.9	0.4	1.5	0.1	0.0	0.3	0.1	1.2
Gas (BP)	53.7	0.6	7.6	8.0	30.8	0.2	0.3	0.4	1.2	1.7	1.0	0.2	0.8	0.1	0.0	0.2	0.1	0.7
Wind (B)	13.1	0.1	1.9	2.0	7.5	0.0	0.1	0.1	0.3	0.4	0.3	0.1	0.2	0.0	0.0	0.0	0.0	0.2
Hydro (B)	14.6	0.2	2.1	2.2	8.4	0.1	0.1	0.1	0.3	0.4	0.3	0.1	0.2	0.0	0.0	0.0	0.0	0.2
Oil (BP)	13.5	0.1	1.9	2.0	7.7	0.0	0.1	0.1	0.3	0.4	0.3	0.1	0.2	0.0	0.0	0.0	0.0	0.2
Other (B)	3.9	0.0	0.6	0.6	2.2	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Solar (P)	1.5	0.0	0.2	0.2	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Land	46.8	46.8																
Capital	4,316.6	61.0	201.0	472.5	3,290.5	8.8	90.9	42.9	17.9	41.8	9.6	16.4	38.4	0.9	2.4	12.1	3.3	6.1
NatlRes	102.8	3.6	3.7			14.9	70.6	10.0										
SkLab	5,852.7	46.5	163.3	475.3	5,117.0	4.3	16.1	6.9	5.9	1.5	0.4	0.1	3.7	0.2	0.0	0.4	0.1	11.0
UnSkLab	4,251.5	11.1	257.1	761.2	3,158.5	4.0	15.1	9.1	9.5	6.0	1.5	0.4	5.2	0.5	0.1	1.2	0.3	10.7

Estimates of Emissions Elasticities

The purpose of this section is to serve as a sensitivity analysis and to propose a more realistic estimate of the elasticities parameters contained in the GTAP database. The behavioral parameters of the model are determinants for the baseline calibration. These elasticities determine how a variable will respond when changing another variable or the degree of substitutability between domestic and imported input.

In this section the model is sequentially re-estimated and two changes are made (assuming new values of the trade elasticities and new values for the share of emissions). The second exercise is particularly important because postulating a functional form and estimate of elasticities for emissions will provide better estimates of the changes in the economic variables of the economy.

To estimate emissions elasticities, the work of Shapiro and Walker (2018) was used. Shapiro presented the estimates of elasticities of substitution for emissions for the manufacturing sector. The formulation used is Exploiting the structural developments in recent geographic literature makes it straightforward to estimate the elasticity parameters. This is because the results of this exercise rely on the value of the parameters of elasticity of substitution across regions for all energy goods. The elasticity of substitution for the energy goods was estimated using fixed effects and maximum likelihood gravity regressions. The dataset includes global coverage of bilateral trade and transport costs for the energy goods (See Table C.3).

Shapiro and Walker (2018, p.3833) defined emissions intensity as a function of the abatement cost and a productivity variable. In its simplest formulation, the form of emissions is (Copeland and Taylor, 2004):

$$e(\varphi) = (1 - a(\varphi))^{\frac{(1-\alpha)}{\alpha}} q \tag{A26}$$

The intensity of emissions in A26 is given by the abatement cost estimated as a direct function of the cost. A dataset was constructed based on data from the United States Energy Information Administration EIA -860 annual reports EIA (2020b), and facility level data from egrid of the EPA Agency (2020a) that related the cost of equipment for abatement of the companies in the form EIA (860) to facility data from the EPA.

As Shapiro and Walker (2018) explains, the exponent sign has to be positive because the intensity decreases with the abatement cost. The dataset was combined with data from the County Business Patterns survey to account for economic activity at the county level. To measure the product, the EIA 860 From reports the gross load values of electricity associated to abatement cost for each of the facilities. The data was only available from 2013 to 2019, so a panel for that time span was constructed.

As Shapiro and Walker (2018) reports, the estimates can be contaminated by three issues: measurement error due to the quality of the data, reverse causality, and the likelihood that the abatement costs reduce because fewer polluting industries are in the market. Therefore, it was necessary to control for economic variables and instrumental variables using the EPA classification of the county for the air quality standards contained in the Green Book (Agency, 2020b). To control for the measurement error, aggregated data was used when possible; if a plant exited the sample then the total gross load of electricity remained. This specification of pollution is consistent with the case presented in the GTAP database. This is a Cobb-Douglas production with constant returns to scale, so the shares are constant.

The elasticity is valid for the United States and is based on a representative number of firms across the whole country. It is representative of the electricity generation sector; generalization of the values should be done with caution since the values are based on the economic condition of the United States.

Table C.2 reports the values of the elasticities for three different pollutants in the data related to plant emissions.

Table C.2. Emissions Elasticities from Electricity Generation

	(1) CO_2 EI	(2) CO_2 EI	(3) ln CO_2 st	(4) ln CO_2 st
Log equipment abatement cost	-0.0045***	-0.0003	0.1250***	0.0668**
	(0.0011)	(0.0007)	(0.0089)	(0.0253)
Primary Fuel Coal	-0.5140***	-0.0885	1.9350***	1.1860*
	(0.0263)	(0.1080)	(0.2060)	(0.5370)
Primary Fuel Gas	-0.9820***	-0.3810**	-0.0965	-0.9030
	(0.0265)	(0.1360)	(0.2070)	(0.5870)
Primary Fuel Oil	-0.6550***	-0.0379	-1.9080***	-2.526***
	(0.0282)	(0.1340)	(0.2210)	(0.5320)
Constant	1.6010***	1.0950***	11.9900***	13.3100***
	(0.0284)	(0.1110)	(0.2220)	(0.5640)
Observations	7,784	7,784	7,784	7,784
Include fixed effects	No	Yes	No	Yes

	(1) SO_2 EI	(2) SO_2 EI	(3) ln SO_2	(4) ln SO_2
Log equipment abatement cost	-0.0002***	0.0001	-0.0037	0.0198
	(0.0001)	(0.0001)	(0.0115)	(0.0356)
Primary Fuel Coal	0.0016***	0.0027*	6.026***	5.323***
	(0.0002)	(0.0013)	(0.2680)	(1.3530)
Primary Fuel Gas	-0.0001	0.0005	-0.8390**	-1.4680
	(0.0002)	(0.0013)	(0.2700)	(1.3930)
Primary Fuel Oil	0.0014***	0.0028	-0.2860	-0.7940
	(0.0003)	(0.0016)	(0.2830)	(1.4650)
Constant	0.0024***	-0.0007	2.119***	2.660
	(0.0003)	(0.0012)	(0.2890)	(1.3680)
Observations	7,898	7,898	7,898	7,898
Include fixed effects	No	Yes	No	Yes

	(1) NO_x EI	(2) NO_x EI	(3) ln NO_x	(4) ln NO_x
Log equipment abatement cost	-0.0020***	-0.0577	-0.0037	0.0198
	(0.0001)	(0.0053)	(0.0115)	(0.0356)
Primary Fuel Coal	0.0016***	0.0023*	6.0260***	5.3230***
	(0.0002)	(0.0009)	(0.2680)	(1.3530)
Primary Fuel Gas	-0.0001	0.00004	-0.8390**	-1.4680
	(0.0003)	(0.0009)	(0.2700)	(1.3930)
Primary Fuel Oil	0.0012***	0.0021	-0.2860	-0.7940
	(0.0003)	(0.0011)	(0.2830)	(1.4650)
Constant	0.0024***	-0.0028	2.1190***	2.6600
	(0.0003)	(0.0009)	(0.2890)	(1.3680)
Observations	7,944	7,944	7,898	7,898
Model controls	No	Yes	No	Yes
Include fixed effects				

Trade elasticities

The numerical exercise in Chapter VII and Chapter VIII presents an update of the trade elasticities included in the GTAP database. Econometric estimation of

Armington functions and COMTRADE data were used to compute the Armington elasticities for the 65 groupings of goods in the database. This was done for the electricity sector and other energy-intensive industries. To match the sectors in GTAP, products were aggregated using the concordances file maps to the six-digit harmonized system (2007) sectors to the original 65-sector GTAP sectoral classification (See (Aguiar, 2016)). This update guaranteed that the parameters for the calibration were been chosen in such a way that they resembled current trade relations between countries (see Table C.2 and Table C.4).

Most CGE models that rely on GTAP data use the values of the parameters reported by Hertel and Van der Mensbrugghe (2016), which are selected based on a review of international cross-sectional studies of various industries and countries. It must be noted the relatively small substitution in the parameters of primary production and the greatest degree of substitutability (1.68) arises in the trade and transport sectors (Hertel and Van der Mensbrugghe, 2016, p. 3). However, estimates of domestic-imported σD value are in the order of 17.20 for gas and 5.20 for oil. It is interesting to compare this to the study by Commission (1992), where the authors reported a value of 0.31. The value is high compared to Huntington et al. (2017), where the values of income price elasticities for highly industrialized economies varied widely by country (between 0.24 and 1.75, averaging 0.94 for all countries) (Huntington et al., 2017, p. 1). A study from 2010 reported estimates of approximately -37.82 for gasoline products (Balistreri et al., 2010, p. 175).

Table C.3. Trade Elasticities

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Coal (COA)				
Log GDP exp	0.156***	-0.114	0.028***	-0.029
	(0.043)	(0.106)	(0.010)	(0.026)
Log GDP imp	0.445***	0.915***	0.093***	0.152***
	(0.039)	(0.105)	(0.009)	(0.025)
Observations	15,563	15,563	15,563	14,541
Panel	3,296	3,296	3,296	2,274
Electricity (ELY)				
Log GDP exp	-3.798*	1.049	-0.259	0.065
	(2.078)	(3.718)	(0.483)	(1.026)
Log GDP imp	0.944	1.970	0.062	0.498
	(2.048)	(2.807)	(0.543)	(0.950)
Observations	336	336	336	262
Panel	177	177	177	103
Gas(GAS)				
Log GDP exp	-0.522***	0.478**	-0.095***	0.038
	(0.080)	(0.222)	(0.015)	(0.041)
Log GDP imp	0.595***	0.760***	0.108***	0.111***
	(0.069)	(0.202)	(0.014)	(0.039)
Observations	6,264	6,264	6,264	5,603
Panel	1,709	1,709	1,709	1,048
Gas manufacture, distribution(GDT)				
Log GDP exp	-0.040	0.383	-0.018	0.211
	(0.088)	(0.442)	(0.047)	(0.245)
Log GDP imp	0.223***	0.338	0.103***	0.144
	(0.065)	(0.325)	(0.035)	(0.174)
Observations	1,665	1,665	1,665	1,244
Panel	738	738	738	317
Oil (OIL)				
Log GDP exp	-0.443***	0.322***	-0.064***	0.019

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Continue next page

Continue Table C.3

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
	(0.052)	(0.118)	(0.009)	(0.020)
Log GDP imp	0.663***	0.115	0.096***	0.015
	(0.049)	(0.132)	(0.009)	(0.023)
Observations	13,272	13,272	13,272	12,254
Panel	3,010	3,010	3,010	1,992
Petroleum, coal products (P_C)				
Log GDP exp	0.403***	0.162***	0.066***	0.016
	(0.018)	(0.047)	(0.004)	(0.010)
Log GDP imp	0.489***	0.507***	0.080***	0.078***
	(0.015)	(0.042)	(0.003)	(0.009)
Observations	84,491	84,491	84,491	81,935
Panel	12,986	12,986	12,986	10,430

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Estimates of Trade Elasticities

The purpose of this section is to describe the procedure utilized to estimate trade elasticities consistent with GTAP data. Elasticities are important because of the need of reflecting actual trading patterns. Need to reflect different trade responses for each sector.

The main data to estimate trade responses came from the UN COMTRADE(Comtrade, 2020). The trade data includes re exports and re imports to be consistent with GTAP database. The database was downloaded as a bulk[1]. and aggregated to match the concordance [2] in GTAP 10 database that corresponds to the GTAP data. The file includes about 5,052 unique trade items that are mapped to 65 GTAP sectors.

[1] https://comtrade.un.org/data/auth/login?ReturnUrl=\%2Fdata\%2Fbulk
[2] https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5111

The mapping uses six digit Harmonized System (2007) sectors to the original 65 GTAP sectoral classification. Also available in TASTE, a program to adapt detailed trade and tariff data to GTAP related purposes [3]. The distance between trade partners is readily available at the *Centre d'Études Prospectives et d'Informations Internationales (CEPII)*[4].

The standard specification of a gravity model was used to estimate the elasticities (CEPII, 2020). The gravity equation simply related trade (exports and imports), GDP of importers and exporters, and distance between trade partners. Because distance is a fixed effect, it will differentiate out in the estimation. I constructed a panel data set and estimated two main specification, a logarithm specification of trade, GDP, and distance using Fixed Effects and Random Effects panel data estimation, and a excess of zeros specification of the Poisson form (a Zero-inflated Poisson regression) (Motta, 2019).

The time spam of the estimation is from 2007 to 2018 to account for the latest trade patterns. The typical logarithm gravity equation is:

$$\ln X_{pt} = \ln GDP_{mt} + \ln GDP_{xt} + D_p + \ln \epsilon_{pt} \tag{A27}$$

where X_p are trade flows for trade pair P. It can be imports or exports, t is the subscript that refers to the year. M is the subscript that refers to importers and X to exporters. ϵ is the error term.

A recent effort of structural estimation was made available trade elasticities for the GTAP database(Soderbery, 2018). Soderbery (2018) used time series methods and a dissagregation to the item level available in the COMTRADE

[3] https://www.gtap.agecon.purdue.edu/resources/taste/taste.asp
[4] http://www.cepii.fr/cepii/en/bdd_modele/bdd.asp

database. Table C.4 presents the results of the estimates of elasticities for all items in GTAP database. The following Table C.3 presents the estimates of trade elasticities that where replaced in the GTAP database to calibrate the baseline.

Table C.4. Trade Elasticities

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Beverages and tobacco products (B_T)				
Log GDP exp	0.553***	0.201***	0.122***	0.050***
	(0.011)	(0.027)	(0.003)	(0.010)
Log GDP imp	0.387***	0.618***	0.078***	0.109***
	(0.009)	(0.024)	(0.003)	(0.009)
Observations	105,872	105,872	105,872	103,456
Panel	14,542	14,542	14,542	12,130
Sugar cane, sugar beet (C_B)				
Log GDP exp	0.124	0.944**	0.030	0.284*
	(0.105)	(0.393)	(0.043)	(0.165)
Log GDP imp	0.085	-0.020	0.037	-0.010
	(0.106)	(0.415)	(0.045)	(0.183)
Observations	1,625	1,625	1,625	1,353
Panel	570	570	570	298

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Continue next page

Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Meat: cattle,sheep,goats,horse (CMT)				
Log GDP exp	0.277***	-0.595***	0.061***	-0.106***
	(0.021)	(0.052)	(0.006)	(0.018)
Log GDP imp	0.336***	0.952***	0.070***	0.170***
	(0.017)	(0.047)	(0.005)	(0.016)
Observations	37,375	37,375	37,375	35,841
Panel	6,358	6,358	6,358	4,824
Coal (COA)				
Log GDP exp	0.156***	-0.114	0.028***	-0.029
	(0.043)	(0.106)	(0.010)	(0.026)
Log GDP imp	0.445***	0.915***	0.093***	0.152***
	(0.039)	(0.105)	(0.009)	(0.025)
Observations	15,563	15,563	15,563	14,541
Panel	3,296	3,296	3,296	2,274
Chemical,rubber,plastic prods (CRP)				
Log GDP exp	0.987***	0.385***	0.188***	0.066***
	(0.008)	(0.019)	(0.002)	(0.006)
Log GDP imp	0.648***	0.553***	0.110***	0.079***
	(0.008)	(0.018)	(0.002)	(0.006)
Observations	177,105	177,105	177,105	174,380
Panel	22,100	22,100	22,100	19,375
Cattle,sheep,goats,horses (CTL)				
Log GDP exp	0.274***	-0.559***	0.063***	-0.105***
	(0.026)	(0.076)	(0.008)	(0.027)
Log GDP imp	0.331***	0.712***	0.074***	0.137***
	(0.023)	(0.062)	(0.007)	(0.021)
Observations	23,002	23,002	23,002	21,913
Panel	4,133	4,133	4,133	3,044
Electronic equipment (ELE)				
Log GDP exp	0.955***	0.347***	0.210***	0.065***
	(0.010)	(0.025)	(0.003)	(0.008)

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Continue next page

Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Log GDP imp	0.596***	0.754***	0.112***	0.120***
	(0.009)	(0.023)	(0.002)	(0.007)
Observations	143,416	143,416	143,416	140,376
Panel	19,421	19,421	19,421	16,384
Electricity (ELY)				
Log GDP exp	-3.798*	1.049	-0.259	0.065
	(2.078)	(3.718)	(0.483)	(1.026)
Log GDP imp	0.944	1.970	0.062	0.498
	(2.048)	(2.807)	(0.543)	(0.950)
Observations	336	336	336	262
Panel	177	177	177	103
Metal products (FMP)				
Log GDP exp	0.891***	0.257***	0.205***	0.054***
	(0.009)	(0.023)	(0.003)	(0.008)
Log GDP imp	0.548***	0.758***	0.106***	0.126***
	(0.008)	(0.022)	(0.002)	(0.007)
Observations	138,954	138,954	138,954	135,946
Panel	18,884	18,884	18,884	15,877
Forestry (FRS)				
Log GDP exp	0.230***	-0.133***	0.054***	-0.035**
	(0.014)	(0.038)	(0.005)	(0.015)
Log GDP imp	0.502***	0.933***	0.128***	0.192***
	(0.015)	(0.039)	(0.005)	(0.015)
Observations	48,692	48,692	48,692	46,826
Panel	8,243	8,243	8,243	6,378
Fishing (FSH)				
Log GDP exp	0.260***	-0.190***	0.069***	-0.033**
	(0.014)	(0.041)	(0.005)	(0.016)
Log GDP imp	0.531***	0.822***	0.140***	0.181***
	(0.015)	(0.043)	(0.005)	(0.017)
Observations	47,058	47,058	47,058	45,234

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Continue next page

Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Panel	7,859	7,859	7,859	6,035
Gas(GAS)				
Log GDP exp	-0.522***	0.478**	-0.095***	0.038
	(0.080)	(0.222)	(0.015)	(0.041)
Log GDP imp	0.595***	0.760***	0.108***	0.111***
	(0.069)	(0.202)	(0.014)	(0.039)
Observations	6,264	6,264	6,264	5,603
Panel	1,709	1,709	1,709	1,048
Gas manufacture, distribution(GDT)				
Log GDP exp	-0.040	0.383	-0.018	0.211
	(0.088)	(0.442)	(0.047)	(0.245)
Log GDP imp	0.223***	0.338	0.103***	0.144
	(0.065)	(0.325)	(0.035)	(0.174)
Observations	1,665	1,665	1,665	1,244
Panel	738	738	738	317
Cereal grains nec (GRO)				
Log GDP exp	0.424***	-0.074	0.087***	-0.009
	(0.025)	(0.063)	(0.007)	(0.018)
Log GDP imp	0.261***	0.424***	0.058***	0.074***
	(0.022)	(0.059)	(0.006)	(0.017)
Observations	33,425	33,425	33,425	31,952
Panel	5,881	5,881	5,881	4,408
Ferrous metals (I_S)				
Log GDP exp	0.763***	0.189***	0.137***	0.017*
	(0.013)	(0.033)	(0.003)	(0.009)
Log GDP imp	0.634***	0.681***	0.105***	0.094***
	(0.012)	(0.030)	(0.003)	(0.008)
Observations	103,238	103,238	103,238	100,487
Panel	14,933	14,933	14,933	12,182
Leather products (LEA)				

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Continue next page

Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Log GDP exp	0.679***	0.358***	0.168***	0.059***
	(0.010)	(0.023)	(0.003)	(0.009)
Log GDP imp	0.619***	0.617***	0.146***	0.124***
	(0.010)	(0.023)	(0.003)	(0.009)
Observations	109,238	109,238	109,238	106,424
Panel	15,565	15,565	15,565	12,752
Wood products (LUM)				
Log GDP exp	0.629***	-0.193***	0.152***	-0.035***
	(0.009)	(0.021)	(0.003)	(0.008)
Log GDP imp	0.602***	1.005***	0.120***	0.178***
	(0.009)	(0.021)	(0.003)	(0.008)
Observations	128,272	128,272	128,272	125,192
Panel	17,984	17,984	17,984	14,906
Dairy products (MIL)				
Log GDP exp	0.373***	-0.587***	0.083***	-0.096***
	(0.017)	(0.038)	(0.005)	(0.014)
Log GDP imp	0.341***	0.620***	0.061***	0.100***
	(0.013)	(0.031)	(0.004)	(0.011)
Observations	62,089	62,089	62,089	60,160
Panel	9,431	9,431	9,431	7,502
Motor vehicles and parts (MVH)				
Log GDP exp	0.935***	0.019	0.203***	0.014
	(0.010)	(0.026)	(0.003)	(0.009)
Log GDP imp	0.500***	0.915***	0.087***	0.140***
	(0.009)	(0.023)	(0.002)	(0.007)
Observations	129,286	129,286	129,286	125,972
Panel	18,578	18,578	18,578	15,265
Metals nec (NFM)				
Log GDP exp	0.651***	0.242***	0.110***	0.032***
	(0.014)	(0.033)	(0.003)	(0.009)
Log GDP imp	0.830***	0.545***	0.152***	0.084***

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Continue next page

Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
	(0.013)	(0.031)	(0.003)	(0.009)
Observations	92,936	92,936	92,936	90,562
Panel	13,175	13,175	13,175	10,801
Mineral products nec (NMM)				
Log GDP exp	0.819***	0.038	0.198***	0.009
	(0.010)	(0.023)	(0.003)	(0.009)
Log GDP imp	0.543***	0.883***	0.104***	0.151***
	(0.009)	(0.022)	(0.003)	(0.008)
Observations	116,625	116,625	116,625	113,751
Panel	16,094	16,094	16,094	13,220
Animal products nec (OAP)				
Log GDP exp	0.434***	-0.165***	0.109***	-0.026**
	(0.013)	(0.034)	(0.004)	(0.012)
Log GDP imp	0.496***	0.542***	0.116***	0.109***
	(0.013)	(0.034)	(0.004)	(0.012)
Observations	64,281	64,281	64,281	62,122
Panel	10,232	10,232	10,232	8,073
Crops nec (OCR)				
Log GDP exp	0.410***	0.289***	0.082***	0.044***
	(0.010)	(0.023)	(0.003)	(0.009)
Log GDP imp	0.581***	0.502***	0.128***	0.095***
	(0.011)	(0.024)	(0.003)	(0.009)
Observations	104,890	104,890	104,890	102,585
Panel	14,476	14,476	14,476	12,172
Food products nec (OFD)				
Log GDP exp	0.642***	0.082***	0.124***	0.017**
	(0.009)	(0.019)	(0.002)	(0.007)
Log GDP imp	0.557***	0.627***	0.097***	0.097***
	(0.008)	(0.018)	(0.002)	(0.007)
Observations	145,109	145,109	145,109	142,492

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Continue next page

Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Panel	18,744	18,744	18,744	16,128
Oil (OIL)				
Log GDP exp	-0.443***	0.322***	-0.064***	0.019
	(0.052)	(0.118)	(0.009)	(0.020)
Log GDP imp	0.663***	0.115	0.096***	0.015
	(0.049)	(0.132)	(0.009)	(0.023)
Observations	13,272	13,272	13,272	12,254
Panel	3,010	3,010	3,010	1,992
Machinery and equipment nec (OME)				
Log GDP exp	1.025***	0.400***	0.201***	0.077***
	(0.008)	(0.019)	(0.002)	(0.006)
Log GDP imp	0.636***	0.736***	0.108***	0.104***
	(0.008)	(0.019)	(0.002)	(0.006)
Observations	182,931	182,931	182,931	180,161
Panel	23,007	23,007	23,007	20,237
Manufactures nec (OMF				
Log GDP exp	0.806***	0.342***	0.204***	0.074***
	(0.009)	(0.022)	(0.003)	(0.009)
Log GDP imp	0.561***	0.635***	0.128***	0.124***
	(0.008)	(0.021)	(0.003)	(0.008)
Observations	132,945	132,945	132,945	129,919
Panel	18,435	18,435	18,435	15,411
Minerals nec (OMN				
Log GDP exp	0.483***	0.229***	0.091***	0.036***
	(0.014)	(0.034)	(0.004)	(0.010)
Log GDP imp	0.626***	0.639***	0.130***	0.110***
	(0.013)	(0.032)	(0.004)	(0.010)
Observations	82,735	82,735	82,735	80,509
Panel	12,063	12,063	12,063	9,837
Meat products nec (OMT				

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Log GDP exp	0.441***	-0.383***	0.104***	-0.056***
	(0.017)	(0.043)	(0.005)	(0.015)
Log GDP imp	0.353***	0.699***	0.070***	0.128***
	(0.014)	(0.038)	(0.004)	(0.013)
Observations	52,150	52,150	52,150	50,254
Panel	8,452	8,452	8,452	6,557
Oil seeds (OSD)				
Log GDP exp	0.212***	-0.039	0.049***	-0.011
	(0.018)	(0.043)	(0.005)	(0.014)
Log GDP imp	0.386***	0.260***	0.100***	0.058***
	(0.018)	(0.046)	(0.006)	(0.015)
Observations	44,898	44,898	44,898	43,155
Panel	7,604	7,604	7,604	5,861
Transport equipment nec (OTN)				
Log GDP exp	0.748***	0.378***	0.144***	0.068***
	(0.015)	(0.041)	(0.003)	(0.010)
Log GDP imp	0.518***	0.790***	0.096***	0.132***
	(0.013)	(0.038)	(0.003)	(0.009)
Observations	98,541	98,541	98,541	95,574
Panel	14,793	14,793	14,793	11,826
Petroleum, coal products (P_C)				
Log GDP exp	0.403***	0.162***	0.066***	0.016
	(0.018)	(0.047)	(0.004)	(0.010)
Log GDP imp	0.489***	0.507***	0.080***	0.078***
	(0.015)	(0.042)	(0.003)	(0.009)
Observations	84,491	84,491	84,491	81,935
Panel	12,986	12,986	12,986	10,430
Processed rice (PCR				
Log GDP exp	0.151***	0.132**	0.034***	0.016
	(0.023)	(0.057)	(0.007)	(0.019)
Log GDP imp	0.061***	0.257***	0.017***	0.047***

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
	(0.020)	(0.055)	(0.006)	(0.018)
Observations	31,322	31,322	31,322	29,891
Panel	5,592	5,592	5,592	4,161
Paddy rice (PDR)				
Log GDP exp	0.007	0.009	0.001	-0.007
	(0.027)	(0.080)	(0.009)	(0.030)
Log GDP imp	0.141***	0.628***	0.044***	0.152***
	(0.025)	(0.082)	(0.009)	(0.032)
Observations	16,668	16,668	16,668	15,565
Panel	3,566	3,566	3,566	2,463
Plant-based fibers (PFB)				
Log GDP exp	-0.187***	0.066	-0.039***	0.014
	(0.022)	(0.061)	(0.006)	(0.021)
Log GDP imp	0.249***	0.342***	0.064***	0.064***
	(0.026)	(0.064)	(0.008)	(0.022)
Observations	23,807	23,807	23,807	22,440
Panel	4,782	4,782	4,782	3,415
Paper products, publishing (PPP)				
Log GDP exp	0.860***	0.270***	0.202***	0.056***
	(0.010)	(0.023)	(0.003)	(0.009)
Log GDP imp	0.503***	0.633***	0.096***	0.104***
	(0.009)	(0.021)	(0.003)	(0.008)
Observations	125,487	125,487	125,487	122,610
Panel	17,056	17,056	17,056	14,183
Sugar (SGR)				
Log GDP exp	0.024	0.100	0.001	0.009
	(0.022)	(0.063)	(0.006)	(0.018)
Log GDP imp	0.176***	0.377***	0.037***	0.068***
	(0.019)	(0.057)	(0.005)	(0.015)
Observations	40,017	40,017	40,017	38,305

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

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Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Panel	7,132	7,132	7,132	5,420
Textiles (TEX)				
Log GDP exp	0.795***	0.462***	0.171***	0.072***
	(0.009)	(0.020)	(0.003)	(0.007)
Log GDP imp	0.651***	0.634***	0.130***	0.105***
	(0.009)	(0.020)	(0.003)	(0.007)
Observations	138,509	138,509	138,509	135,690
Panel	18,485	18,485	18,485	15,669
Vegetables, fruit, nuts (V_F)				
Log GDP exp	0.472***	0.028	0.105***	0.004
	(0.011)	(0.024)	(0.003)	(0.009)
Log GDP imp	0.554***	0.767***	0.113***	0.131***
	(0.011)	(0.025)	(0.003)	(0.009)
Observations	93,052	93,052	93,052	90,529
Panel	13,467	13,467	13,467	10,944
Vegetable oils and fats (VOL)				
Log GDP exp	0.436***	0.105***	0.089***	0.019*
	(0.016)	(0.035)	(0.004)	(0.011)
Log GDP imp	0.344***	0.410***	0.069***	0.071***
	(0.014)	(0.034)	(0.004)	(0.011)
Observations	70,212	70,212	70,212	68,151
Panel	10,483	10,483	10,483	8,427
Wearing apparel (WAP)				
Log GDP exp	0.681***	0.531***	0.161***	0.088***
	(0.009)	(0.021)	(0.003)	(0.008)
Log GDP imp	0.650***	0.753***	0.148***	0.147***
	(0.009)	(0.021)	(0.003)	(0.009)
Observations	125,272	125,272	125,272	122,325
Panel	17,427	17,427	17,427	14,481
Wheat (WHT)				

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

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Continue Table C.4

VARIABLES	(1) PANEL RE	(2) PANEL FE	(3) PPML RE	(4) PPML FE
Log GDP exp	0.353***	-0.113	0.058***	-0.019
	(0.040)	(0.113)	(0.009)	(0.027)
Log GDP imp	0.004	0.498***	-0.002	0.066***
	(0.035)	(0.094)	(0.008)	(0.021)
Observations	17,092	17,092	17,092	16,007
Panel	3,568	3,568	3,568	2,484
Wool, silk-worm cocoons (WOL)				
Log GDP exp	0.054	0.149	0.010	0.028
	(0.035)	(0.092)	(0.012)	(0.034)
Log GDP imp	0.314***	0.374***	0.080***	0.073**
	(0.036)	(0.099)	(0.013)	(0.036)
Observations	8,848	8,848	8,848	8,106
Panel	2,078	2,078	2,078	1,337

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Model Statistics for Chapters VII and VIII

For model documentation and GAMS scripts please refer to CGEBox. Britz and van der Mensbrugghe (2018a) describe in detail how to use and implement simulations using GAMS. The files for the analysis of Chapter VII and Chapter VIII and can be downloaded from:

```
https://www.dropbox.com/sh/njx1100itm3slln/

AADtYRVJT10FGMeDq6oXLDr1a?dl=0
```

```
MODEL STATISTICS (CHAPTER VII)
BLOCKS OF EQUATIONS          116     SINGLE EQUATIONS           610
BLOCKS OF VARIABLES           78     SINGLE VARIABLES           610
NON ZERO ELEMENTS          2,854     NON LINEAR N-Z           1,671
DERIVATIVE POOL               20     CONSTANT POOL            1,175
```

```
MODEL STATISTICS (CHAPTER VIII)
Preprocessed model has 18664 constraints and 18664 variables
with 115114 Jacobian elements, 77906 of which are nonlinear.
```